Zentrum für Entwicklungsforschung

Effectiveness of soil and water conservation measures for land restoration in the Wello area, northern Ethiopian highlands

Inaugural-Dissertation
zur
Erlangung des Grades
Doktor der Agrarwissenschaften
(Dr. agr.)

der Hohen Landwirtschaftlichen Fakultät
der
Rheinischen Friedrich-Wilhelms-Universität
zu Bonn

vorgelegt am 12. Juli 2012

von
SHIMELES DAMENE SHIENE
aus
SHINO, ETHIOPIA

1. Referent: Prof. Dr. Paul L.G. Vlek

2. Referent: Prof. Dr. Armin Skowronek

Tag der Promotion: 05.10.2012

Erscheinungsjahr: 2012

Diese Dissertation ist auf dem Hochschulschriftenserver der ULB Bonn
http://hss.ulb.uni-bonn.de/diss_online elektronisch publiziert

ABSTRACT

Soil-erosion-induced land degradation is a great challenge in the Ethiopian highlands. Consequently, the government has invested in soil and water conservation (SWC) measures, mainly farmland terracing and exclosure of degraded lands. This study analyzed the effectiveness of those measures to tackle land degradation in the North and South Wello zones of the Amhara region (Ethiopia). The study analyzed land use/cover (LULC) and inter-annual normalized difference vegetation index (NDVI) changes based on moderate resolution imaging spectrometer (MODIS) image and NDVI data composited at 8-day and 2-monthly intervals, respectively. The analysis was based on data from 2000 to 2010 covering 300,000 km². The LULC showed remarkable changes, where large decrease in degraded woody vegetation and increases in grassland/woody grassland. Similarly, NDVI showed considerable changes over time where the area covered by NDVI values >0.4 and 0.3 to 0.4 increased by 12.5%, and 2.3%, respectively, which indicate vegetation restoration. Areas along highways, showed a positive NDVI trend, which indicates restoration, while the other parts were identified as degradation hotspots, which could be due to differences in SWC policy implementation. The study also assessed farmland terrace soil fertility and crop yield as well as soil fertility change in exclosures at micro-watershed scale.

Soil fertility change in exclosure was analyzed using soil samples from three age categories (open sites, 10- and 27-year-old exclosures), two agro-ecological zones (*Weyna-Dega*/mild and *Dega*/cool) and three terrain positions (lower, middle and upper). The samples were analyzed for selected physico-chemical properties, and statistically tested with analysis of variance (ANOVA). The results reveal that the exclosure soils showed significantly higher organic carbon (9 g/kg) and total nitrogen (1.2 g/kg) content than those on open sites. However, differences between the 10- and 27-year-old exclosures were non-significant, indicating a decline in fertility restoration rate with age. Exclosures in the *Weyna-Dega* zone showed significantly better soil fertility restoration than those in the *Dega* zone. This might be due to the effect of micro-climate on biomass production, vegetation types and organic matter mineralization. The soil physico-chemical properties neither had significant differences nor followed a regular trend across the terrain of the exclosure, which could be due to mechanical SWC measures. Therefore, exclosure planning should consider soil fertility restoration variation with age, agro-ecology and management.

The farmland terrace soil fertility analysis used composite topsoil (0-20 cm) samples collected from plots representing 4 terrain slope ranges (3-5%, 5-8%, 8-15% and 15-30%) at 3 positions within a terrace and compared with 1983 survey data. The samples were analyzed for selected soil physico-chemical properties and statistically tested using ANOVA. Yield data (grain and biomass) of selected crops monitored between 1995 and 2009 from 40 fixed plots on three terrace positions (low-, mid- and up) were statistically tested by a mixed linear model in SAS. The analysis revealed that farmland terracing helped to maintain soil fertility and crop yield. Crop yields and most soil properties except pH, exchangeable bases and clay content did not show significant differences across the terrain. Unlike in other studies, all topsoil properties except bulk density showed insignificant differences within a terrace, while yields of most crops significantly decreased from low- towards up- terrace position. Gradual bench terrace formation might reduce topsoil fertility gradients within a terrace, but this does not avoid soil depth and crop yield gradients. Soil fertility and crop yield also showed only slight changes (stable yield) across terrace age which indicates that terracing reduced soil and nutrient loss due to water erosion. However, terracing alone does not improve soil fertility and thereby crop productivity. Thus, terracing should be supplemented by soil fertility amendments by considering site-specific conditions. Although SWC measures have limitations, generally they played a significant role in maintaining and/or restoring soil fertility, maintaining agricultural production, restoring vegetation cover, and mitigating anthropogenic land degradation.

Die Wirksamkeit von Boden- und Wasserschutzmaßnahmen bei der Rekultivierung von degradiertem Land am Beispiel des äthiopischen Wello-Hochlands

KURZFASSUNG

Erosionsbedingte Bodendegradation im äthiopischen Hochland stellt eine große Herausforderung an das Landmangement dar. Daher hat die Regierung in Boden- und Wasserschutzmaßnahmen (SWC) investiert, insbesondere in Terrassierung landwirtschaftlicher Flächen und Nutzungsausschluss (Exclosures) von degradiertem Land. Jedoch gibt es keine Studien, die die Auswirkungen dieser Maßnahmen umfassend bewerten. Die vorliegende Studie konzentrierte sich daher auf die Untersuchung der Effektivität der oben genannten Maßnahmen bei der Bekämpfung der Bodendegradation in den North und South Wello Zonen der Amhara Region (Äthiopien). Analysiert wurden Veränderungen der Landnutzung/Landbedeckung (LULC) und inter-annuell Veränderungen des normalisierten differenzierten Vegetationsindex (NDVI) anhand von mittelaufgelösten MODIS-Daten sowie NDVI-Daten, in 8 Tages- und 2 Monatsintervallen zusammengefasst. Die Daten decken den Zeitraum 2000 bis 2010 und eine Fläche von ca. 30.000 km^2 ab. Die LULC- Werte zeigten große Abnahme der Bedeckung in der Landbedeckung, vor allem in degradierter Gehölz-/Strauchvegetation und Zunahme in Grasland/Strauchvegetation. Auch die NDVI-Werte deuten auf eine zeitliche Vegetationsveränderung hin; Flächen mit einem NDVI >0.4 und 0.3-0.4 nahmen um 12.5% bzw 2.3% zu. Flächen entlang der Straßen zeigten einen positiven NDVI Trend, was auf eine Wiederherstellung der Vegetation hindeutet, während andere Bereiche degradierten. Dies könnte die Folge unterschiedlicher Umsetzung der SWC Maßnahmen sein. Desweitern wurden Bodenfruchtbarkeit und Fruchterträge auf terassierten Flächen sowie Bodenfruchtbarkeitsveränderung in den von Landnutzung ausgeschlossenen Gebieten untersucht.

In den Exclosures wurden Bodenproben aus drei Alterskategorien (offene Flächen, 10 and 27 Jahre alte Exclosures), aus zwei agro-ökologischen Zonen (*Weyna-Dega*/mild, *Dega*/kühl) sowie aus drei Hangpositionen (untere, mittlere, obere) physikalisch und chemisch untersucht und anhand von Varianzanalysen (ANOVA) statistisch analysiert. Die Ergebnisse zeigten einen signifikant höheren Anteil an organischem Kohlenstoff (9 g/kg) und Gesamtstickstoff (1.2 g/kg) in den Böden der Exclosures als auf offenen Flächen. Die Unterschiede zwischen den 10 bzw. 27 Jahre alten Exclosures waren jedoch nicht signifikant; dies zeigt, dass die Bodenfruchtbarkeit sich mit dem Alter der Exclosures stabilisierte. Die Böden der Exclosures in der *Weyna-Dega*-Zone zeigten eine signifikant bessere Regeneration als die in der *Dega*-Zone, möglicherweise die Wirkung von Mikroklima auf Biomasseproduktion, Vegetationstyp und Mineralisierung des organischen Materials. Es konnten weder signifikante Unterschiede noch bestimmte Trends in Bodeneigenschaften über die Fläche der Exclosures festgestellt werden, vermutlich eine Folge der mechanischen SWC-Maßnahmen. Bei der Planung von Exclosures sollte daher die Variation in der Bodenfruchtbarkeitswiederherstellung über Alter, Agroökologie sowie Management berücksichtigt werden.

Für die Bodenfruchtbarkeitsanalyse der Terrassen wurden Mischproben (0-20 cm) von Flächen mit vier verschiedenen Hangneigungen (3-5%, 5-8%, 8-15% und 15-30%) von drei Positionen innerhalb einer Terrasse mit Daten aus dem Jahr 1983 verglichen. Der Boden wurde auf ausgewählte bodenphysikalisch-chemische Eigenschaften analysiert und statistisch mit ANOVA überprüft. Ertragsdaten (Körner und Biomasse) aus dem Zeitraum von 1995 bis 2009 von 40 permanenten Versuchsflächen lokalisiert auf den drei o.g. Hangpositionen wurden mit einem gemischten linearen Regressionsmodell in SAS getestet. Die Ergebnisse zeigten, dass Terassierung zu einer Stabilisierung der Bodenfruchtbarkeit und Erträge führt. Weder die Erträge noch die Bodeneigenschaften, ausser Boden-pH, austauschbare Basen und Lehmgehalt,

zeigten signifikante Unterschiede. Im Gegensatz zu anderen Studien zeigten die Bodeneigenschaften, außer Bodendichte, keine signifikanten Unterschiede innerhalb einer Terrasse, während die Erträge der meisten Kulturen von den unteren Terassenstufen zu den oberen signifikant abnahmen. Die allmähliche Bildung von Stufenterrassen könnte demzufolge die Fruchtbarkeitsgradienten des Oberbodens innerhalb einer Terrasse reduzieren, sie vermeidet jedoch nicht Gradienten in der Bodentiefe und in Fruchterträgen. Bodenfruchtbarkeit und Erträge zeigten sehr geringe Unterschiede. Dies deutet daraufhin, dass Terrasierung zu einer Abnahme der Bodenerosion sowie Nährstoffverlagerung über die Fläche führt. Trotzdem reicht Terrassierung als alleinige Maßnahme nicht zur Verbesserung von Bodenfruchtbarkeit und damit von Erträgen aus. Zusätzlich sollten standortspezifische Bodenverbesserungsmaßnahmen durchgeführt werden. Trotz der aufgezeigten Einschränkungen spielen SWC-Maßnahmen eine signifikante Rolle bei der Erhaltung und/oder Wiederherstellung der Bodenfruchtbarkeit, Verbesserung der landwirtschaftlichen Produktivität, Wiederherstellung der Vegetationsbedeckung sowie Verminderung der anthropogenen Landdegradation.

TABLE OF CONTENTS

LIST OF ACRONYMS

ANOVA	Analysis of Variance
ANRS-BFED	Amhara National Regional State Bureau of Finance and Economic Development
ARARI	Amhara Regional Agricultural Research Institute
ARDO	Agriculture and Rural Development Offices
a.s.l.	above sea level
av. P	available Phosphorus
CEC	Cation Exchange Capacity
CSA	Central Statistical Authority of Ethiopian
D_b	Bulk density
DEM	Digital Elevation Model
EC	Electrical Conductivity
EECMY-DASSC	Ethiopian Evangelical Church Mekane Yesus Development and Social Services Commission
EED	Evangelischer Entwicklungsdienst (Church Development Service)
EFAP	Ethiopian Forestry Action Program
EHRS	Ethiopian Highland Reclamation Study
EOC-DICAC	Ethiopian Orthodox Church Development and Inter Church Aid Commission
FAO	Food and Agriculture Organization of the United Nations
FFW	Food-for-work
FRA	Global Forest Resource Assessment
GCP	Ground Control Point
GDP	Gross Domestic Product
GIRDC	Generation Integrated Rural Development Consultants
GPS	Global Positioning System
HDF	Hierarchical Data Format
HSD	Honestly Significant Difference
KGVDP	Kobo-Girana Valley Development Program
LP	Lower-landscape Position
LULC	Land-use/land-cover
MRT	MODIS Re-projection Tool
MOA	Ministry of Agriculture of Ethiopian
MODIS	Moderate Resolution Imaging Spectrometer
MP	Middle-landscape Position
MSCRS	Maybar Soil Conservation Research Site
MT	Metric Ton
NBCBN-RE	Nile Basin Capacity Building Network- for River Engineering
NDVI	Normalized Difference Vegetation Index
NGO	Non-Governmental Organization
NMSA	National Meteorological Services Agency of Ethiopia
NRM	Natural Resources Management
OC	Organic Carbon
OM	Organic Matter
ORDA	Organization for Rehabilitation and Development in Amhara
PA	Peasant Association

SCRP	Soil Conservation Research Program of Ethiopian
SPSS	Statistical Package for Social Sciences
SSA	Sub-Saharan African
SWC	Soil and Water Conservation
TLU	Tropical Livestock Unit
TN	Total Nitrogen
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNESCO	United Nations Educational Scientific and Cultural Organization
Up	Upper-landscape Position
ZEF	Zentrum für Entwicklungsforschung (Center for Development Research)

1 GENERAL INTRODUCTION

1.1 Background and problem statement

Land degradation is a serious global environmental problem. However, wide disparity exists on the extent, depth, type and drivers of the problem (Stocking and Murnaghan 2000; FAO 2004; FRA 2005). A global assessment of human-induced soil degradation (GLASOD) indicated that globally about 560 million hectares (36% of total) of farmlands had degraded at an annual rate of 5 to 6 million hectares (Scherr 1999). Land degradation is severe in developing countries, particularly in Africa, where almost all inhabited lands in Sub-Sahara Africa (SSA) are prone to soil and environmental degradation (Nana-Sinkam 1995; Scherr 1999; FAO 2004; Vlek et al. 2008). Similarly, the natural resource and land degradation in Ethiopia is exceedingly high (Hurni 1993; Shiferaw and Holden 1999). The Ethiopian highlands are most vulnerable to the land degradation problems (Shiferaw and Holden 1999; Dubale 2001). For example, annual deforestation was estimated at about 160,000 to 200,000 hectares (EFAP 1994), and the annual fertile topsoil lost at about 42 t ha^{-1} on crop lands but may also reach up to 300 t ha^{-1} in individual fields (Hurni 1993). Land degradation has a long history in the northern highlands, which were settled 5000 years ago (Hurni 1987; El-Swaify 1997). Wello is one of the highland areas in northern central Ethiopia that is severely affected by land degradation (Woldesemait 1983; Tekle 1999). Carbon dating showed that forest burning in Wello began over 2460 years ago, which indicates a long history of resources degradation (Hurni 1987).

Resources over-exploitation and inappropriate land use such as over-grazing, deforestation, expansion of cultivation and grazing into marginal lands, and backward agricultural practices are considered as the major causes of land degradation (Nana-Sinkam 1995; Stocking and Murnaghan 2000; FAO 2004; FRA 2005). The major driver in Ethiopia is conversion of forest and marginal lands into agriculture due to the growing population pressure together with inappropriate agricultural practices. The Ethiopian population has been growing at a fast rate from 12 million at the beginning of the 1900s to 74 million in 2007, i.e., at a rate of <1.3% before 1950 and 2.6% between 1994 and 2007 (Logan 1946; CSA 2008; Sørensen and Bekele 2009). Due to the favourable climatic conditions, the Ethiopian highlands have a long history of settlement and sedentary agriculture, and as a result the density of the human and livestock population is high (Hurni 1987; Bhan 1988; El-Swaify 1997; Sonneveld and Keyzer 2003). The highlands, which account for 45% of the total country landmass, support about 85% of the human and 75% of the livestock population. In order to secure their livelihoods and feed their livestock, people have exploited the natural resources to a maximum and also used marginal lands for cultivation and grazing (Woldesemait 1983; Hurni 1993). This has resulted in rapid deforestation, severe soil erosion and alarming environmental degradation (Hurni 1993; EFAP 1994; Tefera et al. 2002; Tamene et al. 2006; Nyssen et al. 2009). For example, over 80% of the forest cover was destroyed between 1900 and 1960 (Pohjonen and Pukkala 1990; EFAP 1994). Consequently, the Ethiopia highlands have experienced extensive land-use/land-cover (LULC) dynamics, and in particular, the area of cultivated land has increased rapidly.

The land degradation problem has had serious consequences in Ethiopia such as occurrence of persistent food insecurity, economic losses and various environmental hazards such as recurrent drought (Shiferaw and Holden 1999; Tekle 1999). Deforestation and conversion of marginal land to agriculture has been followed by severe soil erosion that has caused crop production losses, which in turn result in economic losses (Bojö and Cassels 1995). For example, due to soil and nutrient loss through erosion, Ethiopia has been annually losing about US$ 106 million (Bojö and Cassels 1995). To circumvent this problem, the Government of Ethiopia has taken different measures such as policy interventions, conducted studies, and implemented massive soil and water conservation (SWC) and capacity building programs, especially after the severe drought of the failed 1974/75 and 1984/85 rainy seasons (Hurni 1993; Shiferaw and Holden 1999; Tilahun 2006). Soil and water conservation measures were implemented largely in the drought-affected areas, including in Wello (Tekle 1999; Badege 2001). The interventions were focused on both mechanical and biological measures (Tamene et al. 2006; Babulo et al. 2009). The major mechanical measures include construction of bunds, check dams, micro-basins and hillside terraces. The biological measures include enclosure of degraded land from human and animal interferences (exclosures), tree seedling production, planting of tree seedlings on farmlands (agro-forestry), afforestation, and tree plantations around the homesteads and tree plantation in exclosures as enrichment to the natural regeneration (Badege 2001; Feoli et al. 2002; Mekuria et al. 2011). The intention of the interventions was to reduce soil erosion, restore soil fertility, rehabilitate degraded lands, improve micro-climate, improve agricultural production and productivity and restore environmental condition (Vancampenhout et al. 2006; Bewket 2007; Mekuria et al. 2007).

Despite the massive mobilization of resources for SWC, only very few studies have been done to analyze the impacts of the measures with respect to restoration of degraded lands. Beside the insufficiency of the studies, they are also not interdisciplinary, and in some cases the conclusions are contradictory. For example, Bewket (2007) reported that SWC measures were inefficient in reducing soil erosion and restoring soil fertility, while Hengsdijk et al. (2005) criticized the validity of his model. Similarly, Eshatu (2004) reported that planted forest did not result in significant changes in organic carbon, nitrogen and soil-organic matter inputs and did not improved soil fertility during a 25-year forest growth. Conversely, other studies indicated a positive contribution of SWC measures to the reduction of soil erosion, conservation of soil moisture, and restoration of vegetation cover and diversity (e.g., Asefa et al. 2003; Hengsdijk et al. 2005; Vancampenhout et al. 2006; Mekuria et al. 2007; Gebreegziabher et al. 2009). For example, Mekuria et al. (2007) reported significant soil fertility restoration in 5- to 10-year-old exclosures. In spite of these facts, policies, decisions, and planning and implementation of SWC measures have been based on very few case studies and general recommendations of small-scale national level studies like river-basin master-plan development studies. In addition, most plot-based studies are focused on assessing the severity of soil erosion in physical terms and lack information on the impact of SWC on soil fertility and agricultural production. They also have gaps regarding the effect of the service time and difference in agro-ecological and topographic conditions. Furthermore, SWC structures construction demands huge resources (finance, labour, materials and equipment), and the adoption and recommendations of the SWC interventions should be justified by empirically proven evidence (Badege 2001; Amsalu and de Graaff 2007; Nyssen et al. 2007). In order to fill this information gap and support the country’s effort in combating land degradation, a study that assesses the effectiveness and variability of conservation/land management measures is of paramount importance.

1.2 Objectives

The general objective of this study is to analyze the effectiveness of soil and water conservation measures for land restoration in the Wello area, northern Ethiopian highlands. The specific objectives of the study are:

- To analyze the changes in the land use/cover (LULC) and the normalized difference vegetation index (NDVI) in the North and South Wello zones of Ethiopia with the view to assessing vegetation restoration and degradation hotspots;
- To evaluate the performance of farmland terracing in soil fertility and crop yields maintenance and/or improvement in the Maybar watershed, South Wello Zone, Ethiopia;
- To evaluate the performance of exclosure in restoring soil fertility in Gubalafto district (*Wereda)* of North Wello zone, Ethiopia;
- To assess and conduct a synthesis of the implications of SWC measures on land restoration in the North and South Wello zones.

1.3 Organization of the thesis

The thesis is structured in nine chapters. The general introduction, which includes background information, problem statements and research objective, is given in Chapter 1. A literature review and description of the study area including general methodology are given in Chapter 2 and 3, respectively. The analyses are covered in Chapter 4 to Chapter 9. The LULC and NDVI change detection assessing the dynamics with respect to land restoration particularly by exclosure is given in Chapter 4. The impacts of farmland terracing on soil fertility and crop yield are given in Chapter 5 and 6, respectively. The role of exclosure on soil fertility restoration is given in Chapter 7. A synthesis of the implications of SWC measures for restoring degraded land is presented in Chapter 8. Overall summary and conclusions are given in Chapter 9.

2 LITERATURE REVIEW

2.1 Conceptual framework of population growth and land degradation

Water, land and other natural resources are the basis for humans to generate income and produce consumable goods and services (Wallace 2007). Nevertheless, their availability is limited in space and time, and this influences livelihoods, especially of the rural poor who directly depend on them (Antoci et al. 2009). The population density of the developing countries is already higher than the agricultural production of the arable land, which leads to natural resource misuse (Cuffaro 1997). Therefore, population growth, resource management and degradation are central elements for sustainable ecosystem functioning. Conversely, resource deterioration cumulatively leads to environmental and land degradation (Cuffaro 1997; Antoci et al. 2009). There is no agreed theory that adequately addresses the relationship between population growth, resource management and land degradation. The scope and concept of resource management and land degradation are broad and multi-dimensional. Sustainable resources use could determine management practices and priority setting in the processes to fulfill human interests in a given time.

The managers also have different perspectives that could ultimately lead to degradation. For example, soil is perceived and used differently by different managers unless a common management plan is designed. This can be illustrated by the management of soils in a quarry. In the absence of a comprehensive plan concerning sustainable use of the quarry and the topsoil, the use of one could degrade the other (Khater et al. 2003). Hence, planning should consider sustainable use without neglecting the possible potentials. Resources can also be misused by land managers opting for advantages, while a certain practice can result in unintended consequences, e.g., the soil burning (*Guie*) practice in some areas of the Ethiopian highlands. The purpose is to reduce weed infestation and to increase crop yield. However, the practice lead to depletion of soil nutrients such as nitrogen, organic carbon and associated exchangeable bases, and increases soil vulnerability to erosion (Koch and Pülschen 1990).

In Sub-Saharan African (SSA) countries, encroachment on marginal lands due to livestock grazing and cultivation used to be regarded as a means to solve land shortage problems in order to fulfill the basic needs of the growing population (Nana-

Sinkam 1995). The encroachment on less resilient land could cause resource decline within a short period of time (de Sherbinin et al. 2007). He also argued that as the population increases and agricultural land becomes limited, farmers reduce or abandon fallowing. As a result, the land has no time to restore itself through natural processes. Thus, land potential declines with time and can lead to an ecological catastrophe (Turner and Shajaat Ali 1996). Malthus (1798) suggested population check as a remedy to balance the polarity between population growth and agricultural production decline, otherwise natural checks like famines could occur.

Boserup (1965) considered population growth as a positive factor with respect to agricultural production rather than being a threat. The theory argues that population increase could result in efficient labor division and that the additional labor and improved technology have the potential to produce sufficient food for the growing population (de Sherbinin et al. 2007). She pointed out that agricultural intensification, which involves more labor and capital input, could be less harmful as agriculture takes place on suitable land rather than by expanding onto marginal lands. The additional labor gained could also positively contribute to land management through land development practices such as conservation and irrigation. In this case, population increase provides auxiliary labor for conservation activities.

The world population is expected to rise to 9.2 billion in 2050, and growth will be highest in developing countries (UN 2007). The declining farmland holdings and decrease in surplus agricultural production with population increase could erode the food security system through reducing the food reserves for shortfall years (de Sherbinin et al. 2007). The recurrent droughts have worsened the food security situation. In African countries, while the population is increasing (UN 2007), agricultural production has not kept pace (Cuffaro 1997; Nana-Sinkam 1995; Watson and Currey 2009; Bingxin et al. 2010). For example, the agricultural production and population of Ethiopia has to grow by 3.6% annually in order to fulfill the food demand in line with the population growth rate (Sonneveld and Keyzer 2003). This indicates the need for intensification or extensification to narrow the gap. The following framework illustrates the implication of population growth on the limited resources in respect to the two theories (Figure 2.1).

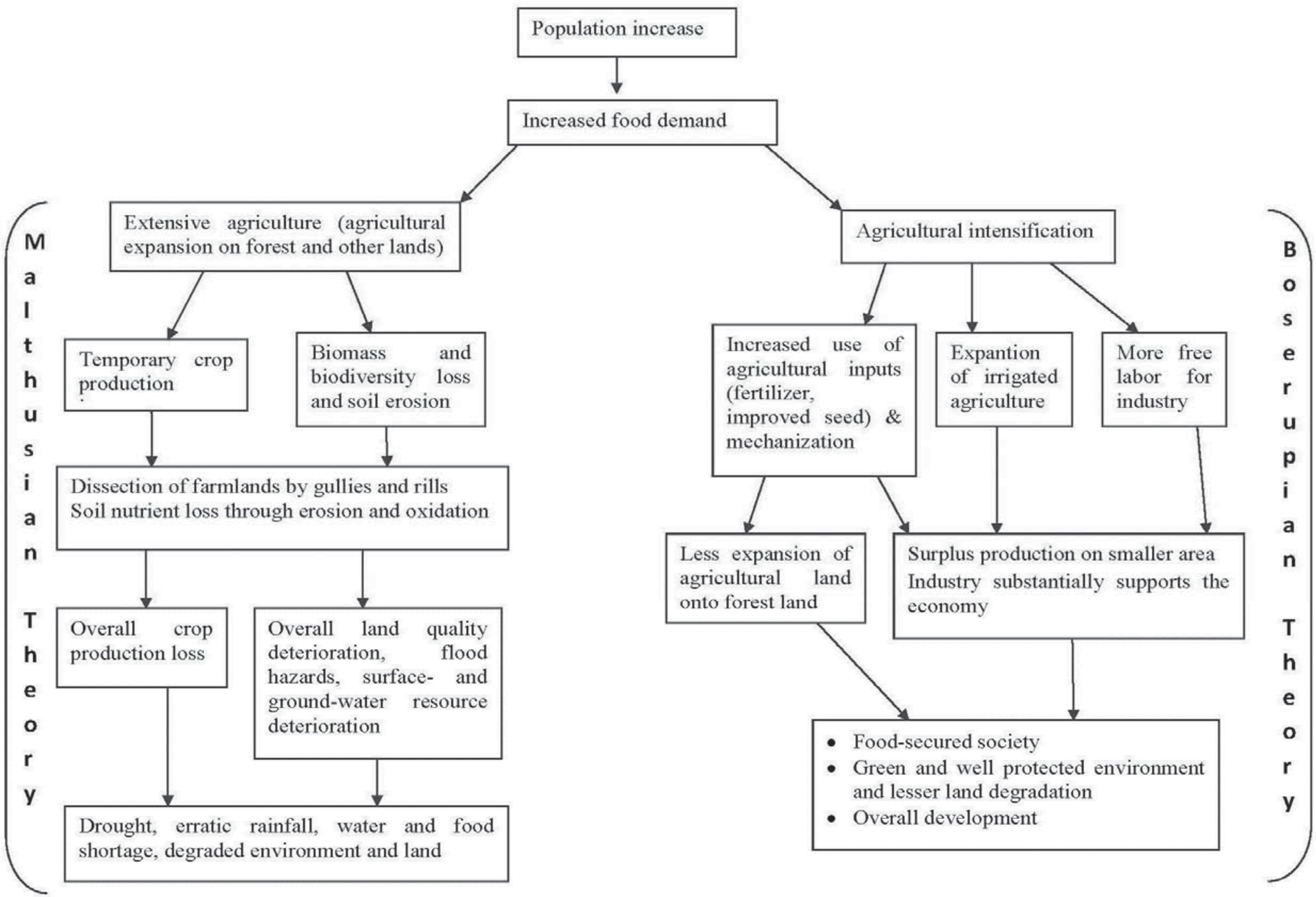


Figure 2.1 Theoretical framework of population growth, agricultural production and land degradation

2.2 Bio-physical conditions and economy of Ethiopia

Ethiopia has a diverse geographical setup, and as a result it has a wide range of bio-physical conditions such as geology, water resources, soils, climate and biodiversity (Tefera et al. 1996; Hurni 1998; Awulachew et al. 2007; Coltorti et al. 2007). For example, the country has geological formations of three categories namely sedimentary, volcanic and metamorphic rocks (Tefera et al. 1996). The topography ranges from depressions below sea level at Danakil to high mountains like Ras-Dashen and other landforms such as plateaus, plains and valleys (FAO 1984; Tefera et al. 1996; Coltorti et al. 2007). As a result, the climate ranges from extreme arid to humid (NMSA 1996; Hurni 1998). Based on agricultural and ecological characteristics, the country can be classified into five agro-ecological zones, i.e., *Berha* (arid), *Kolla* (warm), *Weyna-Dega* (mild), *Dega* (cool) and *Wurch* (cold) (Hurni 1998). The climatic, geological and topographic variability has led to diversified soil types. According to the FAO system of soil classification, more than 18 major soils types have been reported (FAO 1984). The climatic differences have favored a wide bio-diversity (Asefa et al. 2003; Oba et al. 2006; USAID 2008). Thus, Ethiopia is endowed by more than 6000 plant, 280 mammal, 861 bird and 201 reptile species (USAID 2008). It also has a wide range of crop types and a large livestock population of different species. However, only 14% of the land is arable (World Bank 2011). Due to the climatic and geomorphologic conditions, the country has ample ground- and surface-water potential. As a result, Ethiopia is regarded as the water tower of Africa (Awulachew et al. 2007). The potential surface and groundwater and irrigable land is estimated at about 122 billion m^3 and 2.6 to 6.5 billion m^3, and 3.9 million ha, respectively (Awulachew et al. 2007).

Despite the bio-physical resource potential, Ethiopia has been facing a challenge due to land degradation. The land degradation has mainly resulted from improper resource management and traditional agricultural practices (El-Swaify 1997; Lemenih et al. 2005; Nyssen et al. 2009). Deforestation and vegetation clearance were very high to fill the demand for additional cultivable and grazing lands (Puhr and Donoghue 2000; Dubale 2001; Feoli et al. 2002). Replacement of forest and grasslands on marginal lands with cultivation is followed by severe erosion and soil quality deterioration (Richter et al. 1999; Fu et al. 2003; Fu et al. 2008; Kalinina et al. 2009). A large part of the farmlands in the highlands substantially lost its productive potential and a considerable amount (4%) of land reached a point of no-economic-return (FAO 1986). Consequently, agricultural production declined at a high rate (Sonneveld and Keyzer 2003). Annual agricultural production growth is estimated to be about 1.4%, which is much below the population growth rate (2.6%). This indicates that an over twofold gap exists between food demand and agricultural production (Sonneveld and Keyzer 2003; Bingxin et al. 2010; Spielman et al. 2011). Thus, agricultural production rate has to grow from the current level to 3.6% (Sonneveld and Keyzer 2003).

2.3 Agriculture and its challenges in Ethiopia

Ethiopia is an agrarian country on which the economy mainly depends. Agriculture provides 47% of the gross domestic product (GDP), 80% of the employment and 60% of the export commodity (World Bank 2011). Agriculture is mainly in the highlands and is predominantly based on mixed-crop-livestock farming (Haileslassie et al. 2005). The crop and livestock production provides food and export commodities. Of the agricultural product, coffee is the first, and hides and skins are the second main export commodities. Crop and livestock productions support each other, i.e., livestock provide draft power while crop residues are used for livestock feed (Belay and Abebaw 2004; Haileslassie et al. 2005). This is very important for the livelihood and economy of the country (Belay and Abebaw 2004). Generally, the Ethiopian agriculture is characterized by low productivity (Spielman et al. 2011). Crop yields under farmer cultivation are over 50% less than those obtained under improved conditions (Belay and Abebaw 2004). Although chemical fertilizer import increased from 250,000 metric tons (MT) in 1995 to 400,000 MT in 2008, the national average use is only 29 kg ha^{-1} which is mainly used for cereals. The total grain production grew from 5.5 million MT in 1992 to 17 million MT in 2008, but the grain yields increased only by 0.3 MT ha^{-1} during this period, i.e., from 1.1 MT ha^{-1} to 1.4 Mt ha^{-1} (Spielman et al. 2011). This indicates a low input rate and crop production.

Similarly, the livestock sector is also characterized by low productivity (Belay and Abebaw 2004). Low crop and livestock productivity has been attributed to different constraints. Crop production is constrained not only by low input utilization and low technology level but also by land fragmentation and soil erosion (Bingxin et al. 2010; Spielman et al. 2011). In spite of soil nutrient depletion due to soil erosion and crop harvest (grain and residue), the traditional practices that used to maintain soil fertility have almost been completely abandoned (Omiti et al. 1999; Bingxin et al. 2010; Spielman et al. 2011). Traditionally, farmers practice fallowing and apply animal manure that allows fertility restoration. However, due to the population pressure and increasing demand for food and shortage of fuel wood that led to use of animal dung for household energy, and the fallowing practice has been nearly abandoned, which in turn has triggered soil fertility decline and crop productivity loss (Omiti et al. 1999; Haileslassie et al. 2005; Spielman et al. 2011).

Land holdings are also reduced due to frequent redistribution. The per capita land area holding fell from 0.5 ha in the 1960s to 0.2 ha by 2008 (Spielman et al. 2011). Crop production depends on rainfall, but rainfall is erratic in the country. The late start and early stop of rain considerably impacts crop and livestock production and productivity (Tadesse 2001; Tilahun 2006; Descheemaeker et al. 2010). Similarly, livestock production and productivity are limited by poor management, storage systems, and animal health services, and by feed problems (Belay and Abebaw 2004; Descheemaeker et al. 2010). Livestock feed is a critical problem and substantially depends on crop residues (Haileslassie et al. 2005). Particularly the recurring droughts threaten the livestock sector, as animals face feed and water shortages during these dry periods (Belay and Abebaw 2004; Descheemaeker et al. 2010). Although in crop-livestock farming systems, the two sectors complement each other and they also negatively influence each other (Haileslassie et al. 2005). The limited cultivable and grazing lands have resulted in competition between the two sectors. As a result, cultivation and grazing expanded into forest and marginal lands, which aggravated the land degradation processes (Bojö and Cassells 1995; Badege 2001). The above facts illustrate that agricultural production suffers from various constraints. These result in low agricultural production and productivity that triggers inappropriate resource utilization and increases land degradation.

2.4 Land degradation and its implications

Land degradation is defined differently by different authors. Some regard it as a synonym of soil degradation (Stocking and Murnaghan 2000), while others explain the difficulty to define it because of its wider range and scope (Barrow 1991). According to the United Nations Convention to Combat Desertification (UNCCD), land degradation is defined as a natural process or a human activity that causes the land to be unable to provide intended services for an extended time (FAO, 2004). The history of land degradation is as old as the human civilization, and has resulted in irreversible impacts in some cases. For example, the Atacama Desert once was a dense jungle (Kelley 1983). At a global scale, agricultural land lost due to degradation is estimated at about 40% out of which agricultural land in developing countries accounts for the larger portion (FAO, 2004). Developing countries, especially in SSA, have been losing large tracts of land due to this problem (Nana-Sinkam 1995; Scherr 2000; Vlek et al. 2008).

Although there are no well documented or detailed studies concerning land degradation in Africa at the continental level, the few studies conducted at the exploratory level indicate the severity of the problem (Nana-Sinkam 1995; Vlek et al. 2008). Nana-Sinkam (1995) reported that whenever one has the opportunity to travel across various parts of SSA countries, it is easy to see that most inhabited parts are affected by the problem. A study of the FAO also indicated that out of the total land of Africa, 47% is too dry for rainfed agriculture and only 16% of the land has no serious fertility limitation, while the remaining 37% is affected by land degradation (FAO, 2004). The limited agricultural land on the continent has been shrinking due to land degradation. The rate in Africa is estimated at about 230 million ha annually (FAO 2004). A satellite-data-based study also showed that SSA countries that are supposed to have agricultural potential are losing enormous areas of productive land due to the problem (Vlek et al. 2008). As in the other SSA countries, the problem is crucial in Ethiopia (Hurni 1993; Dubale 2001; Nyssen et al. 2004).

Land degradation started as early as the human history of animal domestication and control over fire (Lambin et al. 2003). Human activities have resulted in intended and unintended consequences for the environment. Anthropogenic forest fire was practiced during animal hunting in the earlier ages, and forest clearance for agriculture since recent times. These activities have resulted in a considerable impact on the environment beyond the intended extent and depth (Hurni, 1987; Lambin et al. 2003). The causes of land degradation are complex. Nevertheless, they are similar in many developing countries. Population pressure has been the major driver of the problem (Nana-Sinkam 1995; Tekle 1999; Scherr 2000), and has resulted in extensive conversion of forest and vegetation-covered lands into cultivation and grazing land (Scherr 2000). Conversion of forest and marginal lands to cultivation is followed by severe erosion. It was reported that severe deforestation in Ethiopia occurred between 1900´s and the 1980´s that resulted in a forest cover decline from 40% to 3%, and consequently, soil erosion reached an alarming rate (Pohjonen and Pukkala 1990; EFAP 1994). The annual topsoil loss due to erosion in the Ethiopian highlands is estimated about 1 billion m^3 (Hurni 1993).

The causes and effects of land degradation are complex, and have intermingled environmental impacts (Tadesse 2001). Deterioration of crop production particularly in the highlands is cited as a major and prime impact of the land degradation, where soil and soil nutrient loss due to erosion is a leading cause (Badege 2001; Nyssen et al. 2009). Although the country has huge hydropower and irrigation potential, environmental degradation, particularly erosion and vegetation clearance in the highlands, is threatening this potential (Tadesse 2001; Awulachew et al. 2007). Degradation has also been influencing flora and fauna diversity and negatively impacted the micro-climate (Asefa et al. 2003; Tilahun 2006). Decline of the forest cover also contributed to this problem (Tadesse 2001). In recent times, frequent droughts, early end and late onset of the main rainy (*Kiremt*) season and failure of the smaller rainy (*Belg*) season are linked with climate change and land degradation, which could develop into desertification (Tilahun 2006).

2.5 Land-use/land-cover (LULC) change and its implications

Land use and land cover are interrelated but not synonyms (Jansen and Gregorio 2003). Land use is defined as human modification of a natural environment or wilderness into a new environment such as agricultural fields, pasture and settlement, while land cover is the physical cover of the earth surface that can be grass, water, forest, bare ground, crop field and others (FAO 2000). LULC change occurs due to human and natural drivers. Human-induced changes are associated with socio-economic activities such as agriculture, mining, forestry, forest extraction, wars, settlement and policies. The natural drivers include weather and climatic fluctuations, ecosystem and geological dynamics, and others (Riebsame et al. 1994). Humankind interacts with the environment for its wellbeing, and this determines the change direction to good or bad (FAO 2000; Jansen and Gregorio 2003; Aynekulu et al. 2009). Anthropogenic LULC change began with the time humans used fire and domesticated animals (Lambin et al. 2003). However, there have been rapid dynamics in the past century (FAO 2000). For example, the Global Forest Resource Assessment (FRA 2005) reported 13 million ha annual forest land conversion to agricultural land at a global scale, while reforestation has been taking place at a very slow rate as compared to the net deforestation, especially in Africa (FAO 2000; Jansen and Gregorio 2003).

Archeological studies indicate that Ethiopia was inhabited 3.9 million years back, and people began to use stone tools a million years ago (McPherron et al. 2010). Agriculture in Ethiopia is older than 7000 years (Ehret 1979), oxen-drawn plow-based cultivation began 2000 years ago (McCann 1995; El-Swaify 1997), and forest burning 2460 years ago (Hurni 1987). Thus, the archeological and anthropological studies indicate that human modification of the natural environment in Ethiopia is as old as use of fire, start of agricultural activities and human settlement (Hurni 1987; Tekle 1999). The extent and depth of the LULC change increased with the agriculture expansion, particularly after 1900´s (Pohjonen and Pukkala 1990; Hurni 1993). For example, >80% of the country's forest cover was destroyed within only a little more than half a century between 1900 and 1960 (Pohjonen and Pukkala 1990; EFAP 1994).

The major LULC changes in Ethiopia occurred in densely populated areas, mainly in the highlands (Amsalu et al. 2007; Assen and Nigussie 2009). The changes were mainly conversion of forest and grasslands into cultivation and grazing. With the increasing population, large forest areas were destroyed and converted into agriculture in response to the ever increasing demand for food, grazing land and wood (Feoli et al. 2002; Assen and Nigussie 2009). Limited technology and livelihood options have aggravated the competition between different uses, and government policy and tenure have also played a considerable role (Tefera et al. 2002; Assen and Nigussie 2009). For example, during the emperor period, farmers used traditional shifting cultivation known as *Mofer-zemt Ersha*, where farmers clear forest to get new fertile farmlands (Amsalu et al. 2007; Mekonnen and Bluffstone 2008). This practice was significantly reduced after the 1975 land reform.

On the other hand, the reform made land a state property where farmers were only given farmlands usufruct, while other lands remain public (common) property

(Amsalu et al. 2007). This negatively influenced land management and utilization. Due to the commons, many marginal open areas were cleared to expand cultivation and grazing (Amsalu et al. 2007). After extensive deforestation, the government realized the problems caused by the reform and declared policy measures in 1980s intended to reduce deforestation and restore degraded lands. Nevertheless, there are no studies that adequately address the LULC change in the country (Teferea et al. 2002). Conservation interventions have been also implemented without empirically supported evidence, which could jeopardize their impact (Teferea et al. 2002). Hence, in order to understand the LULC dynamics and design appropriate plans, the use of time-series satellite data is providing a new means of monitoring (Tefera et al. 2002; Vlek et al. 2008). Normalized Difference Vegetation Index (NDVI) dynamics analyses offer a means to track vegetation cover change and, depict environmental changes and provide empirical evidence for decision makers (Jansen and Gregorio 2003; Vlek et al. 2008).

2.6 Vegetation cover change and its implications

Tropical forests are strong carbon sinks, and deforestation of these forests contributes 20% of the total anthropogenic CO_2 emissions to the atmosphere (Baccini et al. 2008). Due to the various difficulties like political instability, limited infrastructure and wide differences in ecology, the aboveground biomass resources of Africa are poorly quantified (Baccini et al. 2008). This hinders quantification of biomass cover and the determination of resources degradation (Zheng et al. 2004; Baccini et al. 2008). Use of remote sensing techniques has paramount significance to minimize this knowledge gap. These data support the quantification of aboveground biomass and forest cover, structure and density (Baccini et al. 2008; Vlek et al. 2008). Satellite-based observations showed that in Africa, pressure on the existing biomass to fulfill the demand for new land for agriculture has been continuing (Baccini et al. 2008; Vlek et al. 2008).

Likewise, land degradation in Ethiopia is largely associated with deforestation and destruction of biomass cover (Badege 2001; Nyssen et al. 2009). Extensive forest resource degradation occurred between 1900 and 1960 (Pohjonen and Pukkala 1990; EFAP 1994) and has continued (Asefa et al. 2003). The leading causes of forest and vegetation destruction include expansion of agricultural land through shifting cultivation and the expansion of sedentary agriculture, increasing demand for construction material, fuel wood and charcoal, and economic dependence of rural households on forest and its products (EFAP 1994; Feoli et al. 2002). A large number of households generate income by selling firewood, charcoal and timber extracted through logging (Feoli et al. 2002). Nearly 82% of the country´s population obtains household energy from fuel wood, and about 13% of the energy comes from animal dung and crop residue (EFAP, 1994). This indicates that biomass directly or indirectly contributes to 95% of the household energy. Beside these factors, negligence (mainly forest fire), recurring droughts, wars, political instability, and lacking land tenure have contributed to accelerated deforestation and habitat degradation (Tefera et al. 2002; Tilahun 2006; Assen and Nigussie 2009). Since the 1970s, Ethiopia has been repeatedly affected by El-Nino events, which cause frequent and extended droughts that influence tree seedlings survival and facilitated forest fires onset (Goldammer 2002; Tilahun 2006; USAID 2008).

Natural resources are interdependent, and degradation of one affects the other. Biomass-cover change influences ecosystem services and processes (Wallace 2007). Ecosystem services acquired from vegetation include provision, regulation, cultural and supporting services (Wallace 2007). Hence, vegetation degradation influences those ecosystem services and processes. For example, vegetation degradation negatively influences soil formation, nutrient and water cycles, climate and erosion regulation, food supply, bio-chemical cycle and others (Wallace 2007). Therefore, the impact of vegetation and forest cover destruction has a wide range of impacts (Richter et al. 1999; Lemenih et al. 2005; Wallace 2007; Kalinina et al. 2009). The recurrent droughts, severe soil erosion, sedimentation of reservoirs and water bodies, soil quality deterioration, surface- and ground-water resource reduction and biodiversity loss are some of problems related to deforestation and vegetation clearance (Asefa et al. 2003; Lemenih et al. 2005). Vegetation cover degradation has also threatened the bio-diversity potential, and the plant seed reserve has also become eroded due to surface cover clearance and soil degradation (Asefa et al. 2003; Khater et al. 2003; Wassie et al. 2009).

2.7 Soil erosion and its consequences

Soil erosion is both natural (geological) and through human induced processes caused by two agents, water and wind. Geological erosion occurs under natural conditions, where the soil loss is positively balanced by soil formation that indicates net gain (El-Swaify 1997; Kaihura et al.1999). However, soil loss due to accelerated erosion is very much higher than the soil gain through parent material weathering. Water erosion is a common phenomenon in humid environments but is increasingly an issue in semi-arid regions due to the increased incidence of intense storms. Wind erosion predominantly occurs in arid and semi-arid areas (Dregne 1990; Nana-Sinkam 1995). Erosion is a major challenge particularly in SSA countries (Nana-Sinkam 1995).

Ethiopia is one of the SSA countries most severely affected by the problem, and water erosion is prominent. Water erosion mainly occurs in the highlands, which have erratic rainfall generating erosive runoff (Hurni 1993). Various studies provided empirical evidence of the severity of the problem. For example, the Ethiopian highland reclamation study (EHRS) estimated 1.9 billion tons annual topsoil loss from the highlands due to water erosion, which is equivalent to 8 mm soil depth or 130 t ha^{-1} annual losses. The study also indicated that out of the total highlands, 50% was significantly eroded, 25% was seriously eroded, and 4% had reached a point of no economic use (FAO, 1986). Hurni (1993) also reported as much as 300 t ha^{-1} annual soil loss from croplands with average rates of 42 t ha^{-1}. Similarly, Herweg and Ludi (1999) estimated a higher than 110 t ha^{-1} annual soil loss from farmlands without terraces.

On the other hand, the annual soil formation of the Ethiopia highlands is estimated to be between 2 and 22 t ha^{-1} and varies with geologic and climatic conditions, topographical setup and agricultural practices (Hurni 1983). Soil erosion varies with soil types (erodibility) and erosive factors like slope of the land (length and steepness), rainfall characteristics (volume, intensity and duration), soil cover and land management (Prasannakumar et al. 2012). Among the soil types, Luvisols and Nitosols were found to be most vulnerable to water erosion, while Vertisols and Phaeozems were less vulnerable (Herweg and Ludi 1999). The same study indicated that rainfall erosivity and very high erosion rates were observed in high rainfall areas. This is in line with the estimation by Prasannakumar et al. (2012) using a universal soil loss model. This indicates that in the Ethiopian highlands, soil formation is much lower than the erosion rate. Due to erosion, farmlands in many parts of the highlands have shallow soil depths and poor fertility (Shiferaw and Holden 1999; Ciampalini et al. 2008). The traditional agricultural practices and inappropriate land use have aggravated the erosion processes (Tamene et al. 2006; Ciampalini et al. 2008; Nyssen et al. 2009). The impact of soil erosion is complex leading to reduction in soil depth and moisture storage capacity together with soil-nutrient losses, and ultimately results in reduced agricultural production and productivity (Vancampenhout et al. 2006). Soil erosion is a threat not only to agriculture but also to the economy, as the country´s economy depends on agriculture.

2.8 Practices and implications of soil and water conservation in Ethiopia

People were already aware of the negative consequences of soil erosion on agricultural production and the environment centuries ago. As a result, soil and water conservation practices exist as indigenous knowledge in some areas of Ethiopia (Nyssen et al. 2007; Watson and Currey 2009). For instance, the Konso people in southern Ethiopia are known for traditionally well developed terraces, where the terrace practices are registered by the United Nations Educational, Scientific and Cultural Organization (UNESCO) as a world heritage. The Konso terraces are estimated to be older than 400 years. Some rudimentary and poorly established terraces and lynchets depicted on older aerial photographs and physical remnants can also be observed in different parts of the northern highlands. For example, Nyssen et al. (2007) reported old lynchets in the Tigray region (northern Ethiopia). This is an indication of indigenous knowledge on SWC practices, and terracing is not only limited to the Konso area but is also found in other parts of the country. However, the SWC in Ethiopia covered very few areas and most of them, except those in Konso, have limitations in layout and construction quality (Nyssen et al. 2007; Watson and Currey 2009).

As the government realized the problem of land degradation, it took policy actions. In this regard, a forest and wildlife conservation and development policy was declared in 1980 (Anonymous 1980). Following this policy, the government initiated various studies and capacity-building programs and massive SWC interventions (Herweg and Ludi 1999; Shiferaw and Holden 1999; Tekle 1999). The capacity-building programs involved training of professionals at the national level and farmers on the local. In this regard, SWC was included in the university curriculum, and the mandate to train farmers was given to the Ministry of Agriculture. SWC interventions in the highlands focused both on mechanical and biological measures (Tekle 1999; Tamene et al. 2006; Babulo et al. 2009). The mechanical measures included construction of bunds, terraces, diversion ditches, check dams, micro-basins and hillside terraces. The biological measures comprise enclosure of degraded land from human and animal interference (exclosure), tree seedling production, agro-forestry tree seedling planting on farmlands, afforestation, and tree planting at homesteads and in exclosures as tree enrichment (Nyssen et al. 2009; Mekuria et al. 2011). In the highlands, drought-affected areas such as Harerghe, Wello, Gonder, north Showa, Tigray and north Omo were targeted (Herweg and Ludi 1999; Amsalu et al. 2007; Mekuria et al. 2011). In order to support the SWC interventions, six research sites (Hunde Lafto, Maybar, Andit Tid, Anjene, Gununo and Dizy) were established and research has been taking place there (Herweg and Ludi 1999). These sites represent different agro-climatic, soil, geomorphologic and farming practices (Shiferaw and Holden 1999; Herweg and Ludi 1999).

Initially, the SWC activities were carried out using food aid in the form of food-for-work (FFW); however free community labor was mobilized as the people´s awareness increased (Tekle 1999; Badege 2001). The basis for the implementation of the SWC interventions on a large scale was the 1975 land reform and the establishment of peasant associations (PAs). The reform gave farmland usufruct to the farmers that motivated them, and the PAs facilitated implementation of SWC and played an instrumental role for labor mobilization (Shiferaw and Holden 1999; Bewket 2007). The SWC interventions showed an inconsistent adoption trend over time. Initially, farmers viewed the structures as showing limitations, as they were not getting immediate returns (Amsalu et al. 2007). Among the limitation farmers mentioned were that the mechanical structures on farmlands reduced the area of cultivable land, harbored rodents, and the construction was labor intensive (Amsalu and de Graaff 2007). Despite the problem of soil erosion and poor soil fertility, this perception of SWC is to be taken seriously because farmers have small and fragmented farmlands (Shiferaw and Holden 1999; Amsalu and de Graaff 2007). Amsalu and de Graaff (2007) reported that larger farms with less livestock, on steep slopes and with poor fertility adopted the practice better than those with contrasting conditions.

The rural land administration and use policy declared in 2005 is an indication of the government commitment to follow up on the previous initiatives. The policy enforces proper land use, and gives clear demarcation based on slope of the land (Anonymous 2005). The aim of the current interventions is not only *in-situ* soil conservation but also protection of giant hydropower dams against sedimentation, e.g., the dam on the River Abay (Blue Nile). The Nile tributaries originating from the Ethiopian plateau annually carry about 180 million tons of sediments (NBCBN-RE 2005). The sediments threatened reservoirs downstream, where some have been annually losing nearly 1% of their capacity (NBCBN-RE 2005). The SWC interventions have positive impacts such as reducing runoff and soil erosion through reducing the first two erosion processes (detachment and transportation), improving basin hydrology, maintaining and/or improving farmland soil fertility and thereby improving/maintaining agricultural production, reducing sediment load to natural and human-made reservoirs and reducing further degradation (NBCBN-RE 2005; Nyssen et al. 2006; Vancampenhout et al. 2006).

2.9 Land degradation and SWC practices in North and South Wello zones

The North and South Wello zones are among most strongly affected by soil-erosion-induced degradation and droughts in the northern highlands (Dejene 1990; Hurni 1993; Tekle 1999). Most bio-physical conditions of the area such as climatic, geomorphologic and geo-hydrologic characteristics, human and livestock population and agricultural practices exacerbate soil erosion and land degradation. The diversified topographic setup, which ranges from lowland valley plains to very high mountains and deeply incised gorges, resulted in a complex drainage system, which facilitates degradation processes. Bhan (1988) reported that the Wello zones, particularly areas with elevation >2000 m a.s.l., have a high erosion risk. Climatic differences, particularly rainfall and temperature, influence the bio-physical features such as soil formation and erosion and biomass production and diversity (Gonfa 1996). Soil erosion is severe in the *Weyna-Dega* (mild) and *Dega* (cool) zones, which mainly have rugged topography and cover over 83% of the area. In Wello, people probably settled 5000 years ago (Hurni 1987; El-

Swaify 1997) and charcoal samples carbon dating indicated that forest burning began 2460 years ago. These indicate old history of forest burning and anthropogenic environmental influence. The old settlements and growing demand for wood and agricultural lands and traditional agriculture led to heavy deforestation and severe erosion in the area (Hurni 1987; Tekle 1999). The ill-suited agricultural practices such as up-and-down and repeated plowing facilitate severe erosion (Hurni 1987).

Owing to high human population, the land-holding size is below the minimum (1 ha per household) and the livestock population (about 76 TLUs km^{-2}) exceeds the carrying capacity of the land (Tekele 1999). For example, the population of South Wello grew at an annual rate of 3.37% between 1970 and 1994, and 1.43% between 1994 and 2007, i.e., the population was 1,174,600 in 1970, 2,123,803 in 1994 and 2,519,450 in 2007 (Tekle 1999; CSA 2008). Although agriculture is the major economic sector, it is still traditional (Ehret 1979; McCann 1995). The agriculture is largely based on cereal-livestock farming systems (ANRS-BFED, 2008) where they have complimentary and competitive effects to each other (Haileslassie et al. 2005). Farmlands used to supply crop residue as animal feed without putting manure back to farmlands while fallowing practices have been greatly reduced. These increased soil-nutrient export out of the ecosystem, exacerbates the degradation processes and contributed to crop production loss (Omiti et al. 1999; Haileslassie et al. 2005). Due to the above numerous limitations and increasing demand for agricultural land, marginal lands have been converted to cultivation and grazing (Tekele 1999). As a result, agriculture in the region has been unable to provide sufficient food for its population. Thus, food insecurity remains persistent, which indicates the need for continued remedial measures (Bhan 1988; Dejene 1990; Tekle 1999). It has been reported that if the resources are not managed according to the potential, land degradation problems will remain cyclic (Bhan 1988; Tekle 1999).

After the droughts, the Wello province received government attention, which led to the initiation of SWC measures (Dejene 1990; Tekle 1999). Consequently, research, capacity-building trainings and SWC projects were implemented. The SWC measures have been implemented on farmlands and communal lands. Farmlands received mainly terraces and check-dams. Communal lands are used for free livestock grazing and wood collection, and first mechanical structures such as hillside terraces, micro-basins, cutoff drains and trenches were constructed, and then these lands were excluded from human and animal interference. The vegetation cover of these exclosures improved through enrichment tree plantation. However, the major concern in this regard is that the enrichment tree plantations are mainly covered by eucalyptus, while indigenous tree species have been significantly reduced (Eshatu 2004; Tekle 1999). The agriculture offices are responsible for overall coordination, monitoring, technical guidance and implementation of the program, while local and international NGOs support the program through finance, FFW commodities, logistics and project implementation (Herweg and Ludi 1999; Tekle 1999).

3 STUDY AREA AND GENERAL METHODOLOGY

3.1 Study area

3.1.1 Location

Ethiopia is located on the horn of Africa between 3° and 15° N latitude and 36° and 48°E longitude (Figure 3.1) covering about 1.13 million km^2. The country is divided into nine national regional states and two city administrations. The national regional states are Amhara, Afar, Benishangul-Gumz, Gambela, Harari, Oromia, Somali, Southern Nation Nationalities and People´s and Tigray. The city administrations are Addis Ababa and Dire Dawa. The regional states are further subdivided into zones, and the zones are again subdivided into *Weredas* (districts). The administrative structure below the *Wereda* is the *Kebele*. In most rural areas in Wello, a *Kebele* administers about 1000 households.

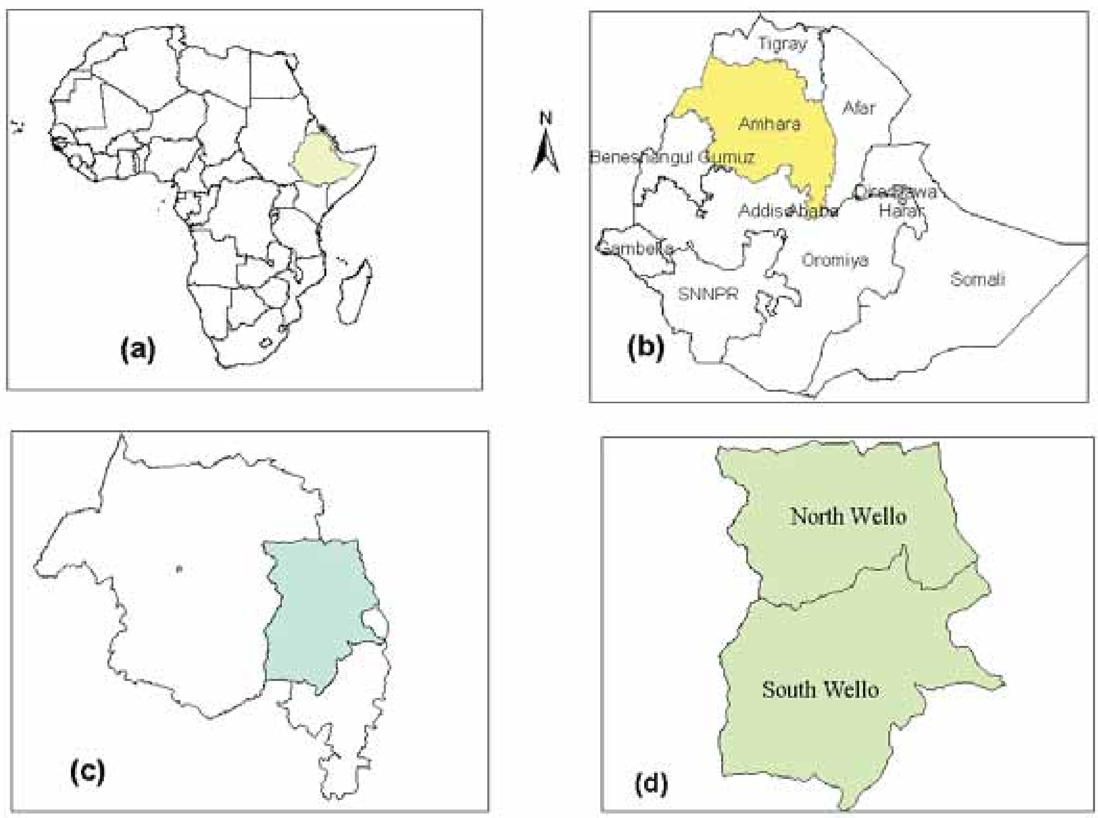


Figure 3.1 Location of study area: (a) Ethiopia in Africa, (b) National Regional States of Ethiopia, (c) Wello in Amhara region, and (d) North and South Wello zones

This study was conducted in the North and South Wello zones in the Amhara National Regional State. The zones are located in the eastern part of the region. The capitals of the South and North Wello zones are Desse and Weldiya, respectively. Desse and Weldiya are about 410 km and 520 km north of the Ethiopian capital, Addis Ababa, respectively. The two zones are located between 10°12' to 12°22' N latitude and 38°30' to 40°14' E longitude and cover about 30,000 km^2.

3.1.2 Bio-physical characteristics

Climate

According to the local system, the country is classified into 5 agro-ecological zones: *Wurch, Dega*, *Weyna-Dega*, *Kolla* and *Berha* (NMSA 1996; Hurni 1998). In the study area, the *Kolla*, *Weyna-Dega*, *Dega* and *Wurch* zones cover 8.5%, 44.8%, 38.5% and 8.2% of the area, respectively (Figure 3.2). Based on Koppen´s classification, the Wello area is classified in three climatic regions: cool highland climate, tropical climate with dry summer, and tropical climate with distinct dry winter. Wello also has three distinct seasons namely *Bega, Belg* and *Kiremt*. *Bega* is a dry season from October to January (NMSA 1996). *Belg* is the small rainy season that occurs between mid February and mid May, while *Kiremt* is the main rainy season that extends from mid June to mid September (NMSA 1996). The mean annual temperature and mean annual rainfall ranges from 14°C to 20°C and from 680 mm to 1200 mm, respectively (Gonfa 1996). Based on the moisture index, the climate of Wello is classified as dry with arid to dry sub-humid conditions. According to the climatic characteristics, the region is further subdivided into an eastern and western part. Eastern Wello has a relatively dry climate with a moisture index of minus 60 to 0, and most areas receive sufficient moisture during the rainy seasons with some surplus water. In contrast, western Wello has a moderate to large amount of water surplus in the rainy seasons, which results in high run-off, soil erosion and water-logging depending on the soil type and topography (Gonfa 1996).

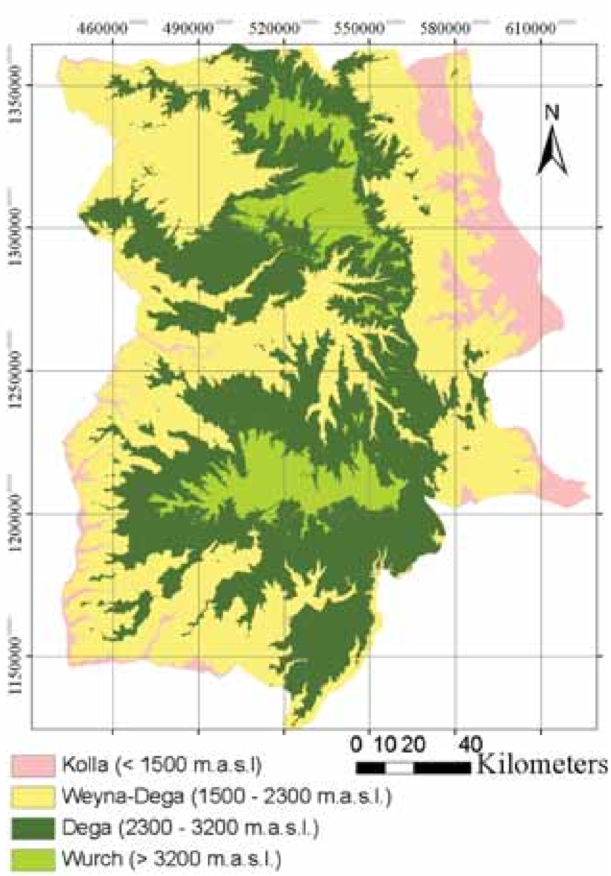


Figure 3.2 Agro-ecological map of North and South Wello zones

Topography

The digital elevation model (DEM) reveals that larger parts of Wello are characterized by rugged topography that consist very high mountains, deeply incised canyons and gorges, valleys and plateaus (Figure 3.3). The rugged topographic condition of the area was also reported in other studies (e.g. FAO 1984; Tefera et al. 1996; Coltorti et al. 2007). Due to the strong relief differences, anthropogenic activities have led to extensive degradation. The highest (4220 m) and lowest (900 m) elevations are in the South Wello zone. The lowest areas are in the Rift Valley, which is part of the East African rift system. The DEM analysis also indicates that the areas covered by slopes < 2%, 2 to 15%, 15 to 30% and >30% cover 2%, 30%, 28% and 40 % of the total area, respectively. Land with slopes less than 15% is most suitable for agriculture (Hurni 1988). However, this area accounts for only 32% of the total area.

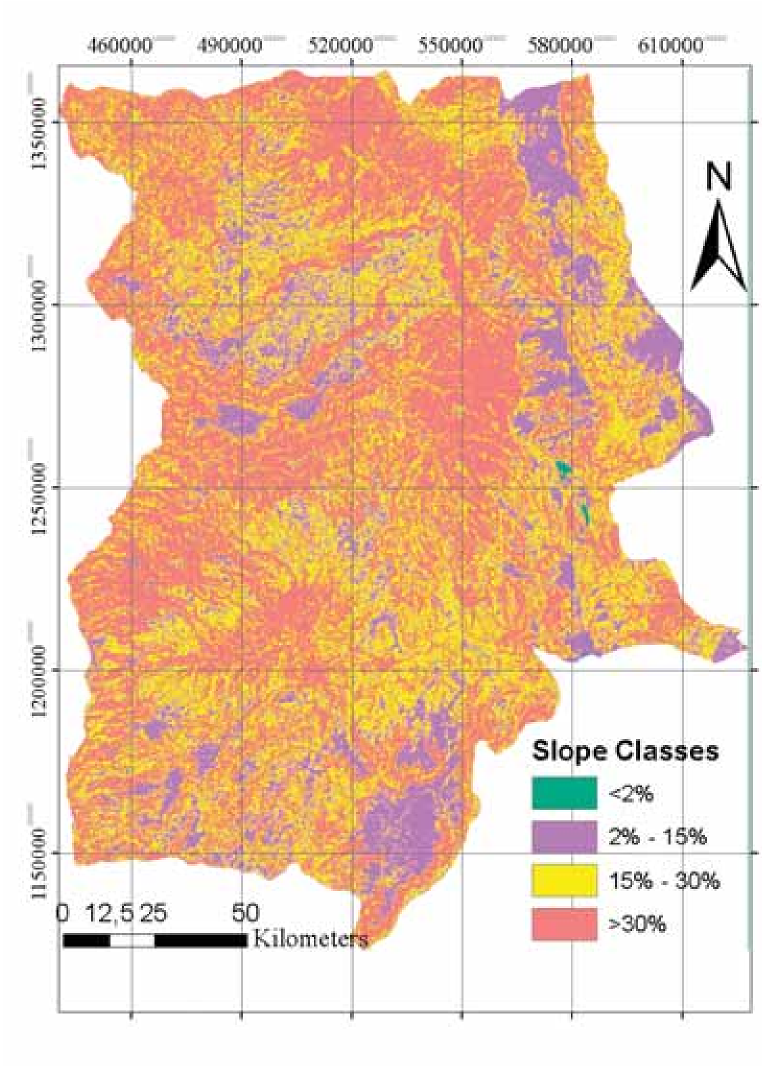


Figure 3.3 DEM slope map of the North and South Wello zones

Geology

Wello is covered by Cenozoic volcanic rocks with some sedimentary rocks (Figure 3.4). The Cenozoic volcanic rocks have developed from tertiary flood basalt sequences with intercalation of felsic lava and pyroclastic rocks up to 3 km thick. The Cenozoic volcanic rocks and the associated sedimentary rocks are further subdivided in various formations. The major formations are Ashangi, Tarmaber-Megezez, Alajae, Aiba basalts and Amba-Aradom formations covering 49%, 18%, 14%, 12% and 3%, respectively (Tefera et al. 1996).

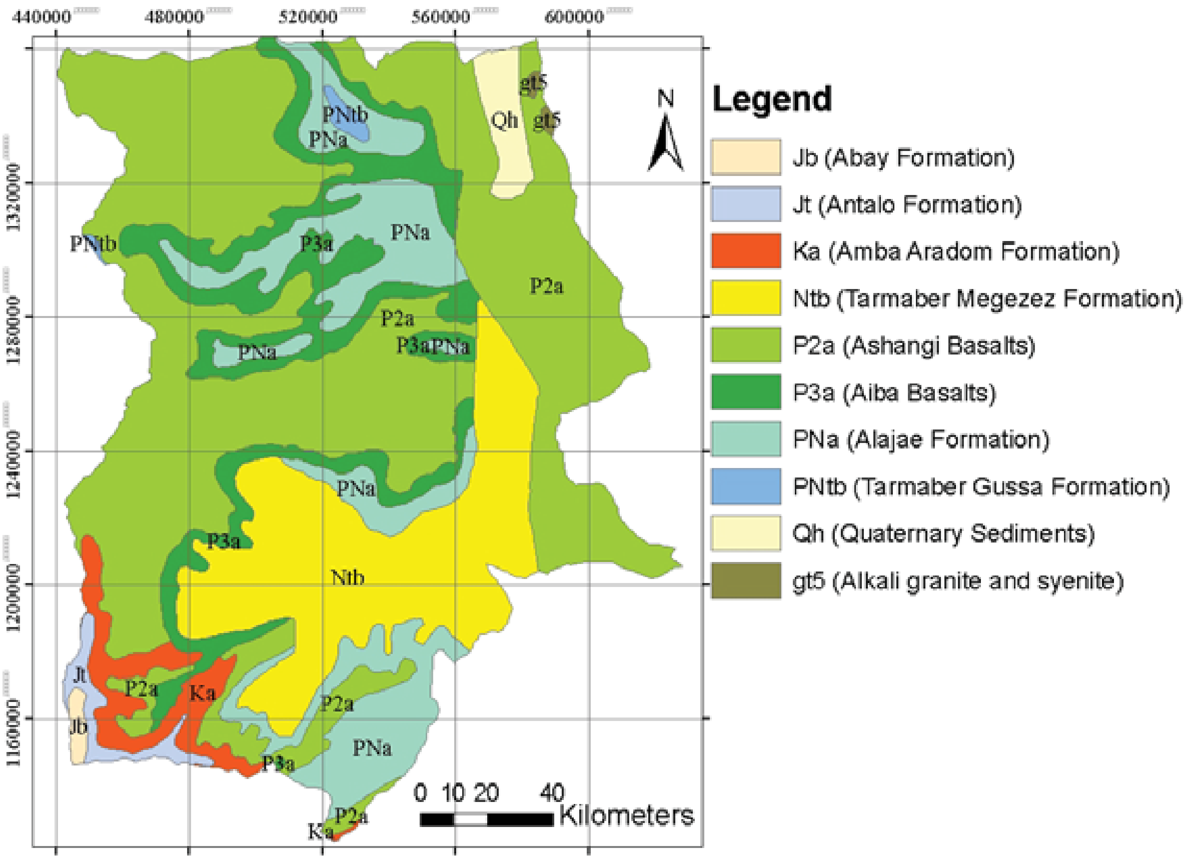


Figure 3.4 Geological map of North and South Wello zones (Tefera et al. 1996)

The other formations such as quaternary sediments, Antalo, Abay, Tarmaber-Gussa and Alkali granite and syenite formations cover about 4% (Tefera et al. 1996). Ashangi formations are deeply weathered alkaline and transitional basalt within rare intercalations. Tarmaber-Megezez formations are transitional and alkaline basalt, while the Alajae formation mainly consists of aphyric flood basalts associated with rhyolites (ignimbrites) and subordinate trachytes. The Aiba basalts are pulse of fissural basalt volcanism, which are generally aphyric, compact rocks, in place showing stratification and containing rare inter-bedded basic tuffs. The Aiba basalts unconformably overlay the Ashangi formation, which is as thick as 200 to 600 m. The Amba-Aradom formation consists of sandstone, shale and marls that conformably overlies the Antalo formation (Tefera et al. 1996).

Soils

Wello has various soil types, the major soils being Leptosols, Cambisols, Vertisols, Andosols and Luvisols (FAO, 1984). Leptosols are the dominant soil types, which cover

over 35% of the study area and followed by Cambisols, Vertisols, Andosols and Luvisols (FAO, 1984). Leptosols are shallow, mostly brown or yellowish brown and clay to clay loam. Leptosols are characterized by common to abundant surface stoniness, few to common rock outcropping and many coarse fragments throughout the profiles. At the second level, the Leptosols are further classified into Eutric, Dystric and Lithic. Cambisols are further classified as Vertic and Dystric. Cambisols have wide physical, chemical and morphological characteristics and are shallow to moderately deep. Vertisols in the study area are moderately deep to very deep on flat to almost flat lands. They are characterized by dark to dark gray color, clayey texture, poor drainage and workability, and develop wide and deep cracks upon drying and swell upon wetting. The Vertisols of Wello are further classified into Euthric and Calcic. Luvisols occur in cooler areas in very small parts and on gently sloping lands. They are well drained, brownish in color, clayey textured, have high CEC (>24 cmol/kg clay) and higher base saturation, mostly >50%. Andosols cover small parts of the study area in the Rift Valley and the escarpments towards the valley. They are shallow to very deep, clayey textured and have a high pH (pH >7) (FAO, 1984).

Hydrology

The study area drains to three major river basins of the country and to a river that sinks within the study area. The rivers are Abay (Blue Nile), Tekeze, Awash and Golina (Figure 3.5). Tekeze River joins the Blue Nile at Atbara in Sudan. The Tekeze and Golina drain the northwest and northeast parts, respectively, while the other parts are drained by the Abay and Awash rivers. The Abay, Tekeze, Awash and Golina rivers drain 17550 km^2, 5265 km^2, 4385 km^2 and 2770 km^2, respectively. The concentrated drainage network and the closely spaced watershed divides indicate dissected topographic characteristics and possibility of intensified differential erosion. The intense drainage systems and steep slopes also indicate vulnerability of the area to erosion and degradation, if there is improper anthropogenic intervention.

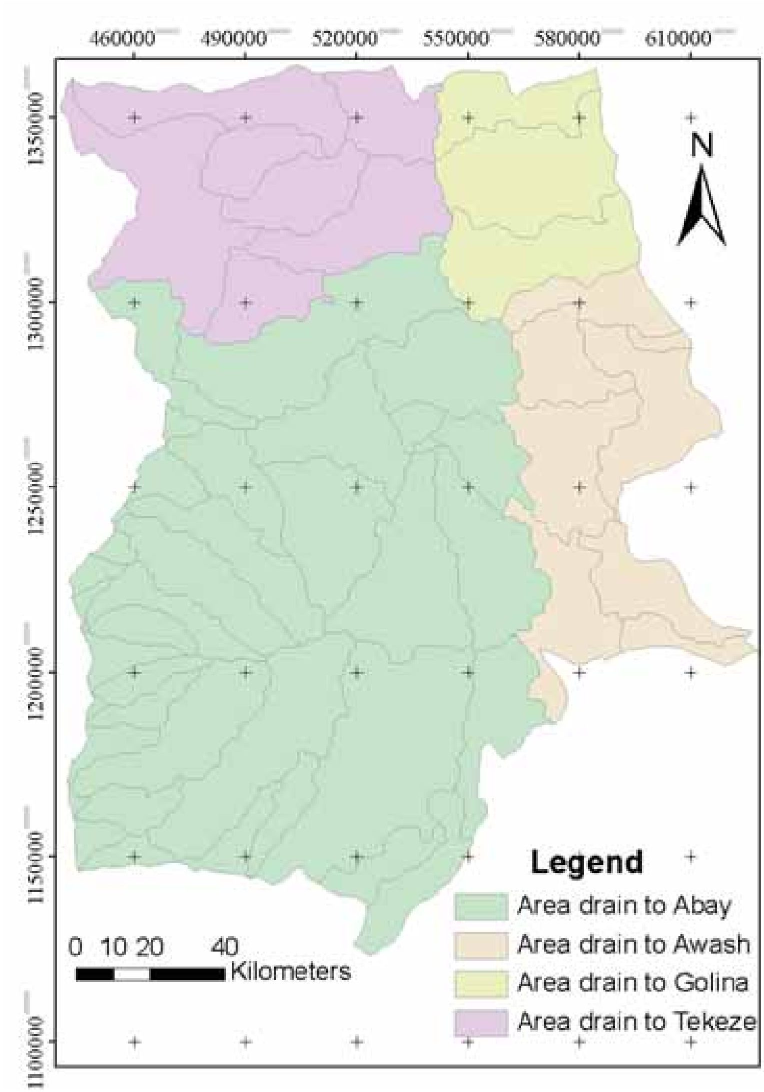


Figure 3.5 Drainage systems of North and South Wello zones

3.1.3 Agriculture and farming system

The main livelihood base and economy of the Ethiopians is agriculture. Like other parts of the Ethiopian highlands, the major farming system of Wello is mixed cereal-livestock (Haileslassie et al. 2005). The farming system is diversified and determined by agro-ecology. Cereals are the dominant crop accounting for over 73%, followed by pulses (24%) and the remaining 3% is oilseed (ANRS-BFED 2008). Among the cereal crops teff, sorghum, wheat and barley are dominant, accounting for 25%, 18%, 16% and 11% of the total, respectively (ANRS-BFED 2008). Horse bean, lentil, chickpea and field bean are the major legume crops accounting for 16% of the total crop production (ANRS-BFED 2008). Farmers rotate cereals with legumes to maintain soil fertility and crop yield. Like in other parts of the country, the farming system and farm implements are traditional and inherited from indigenous knowledge (Ehret 1979). The traditional tillage implement known as *Maresha* is an ox-drawn plough, which has been used for more than two thousand years (Ehret 1979; McCann 1995). Traditional re-tillage practices, known as *Shilshalo*, are usually performed about six weeks after maize and sorghum sowing. *Shilshalo* has various purposes such as harrowing, which improves soil air, water and nutrient circulation, root development, and uproots and kills weed and optimizes plant density. The traditional up and down cultivation across the slope of the land practiced for centuries has led to severe soil erosion and land degradation. Weeding and harvesting is manual.

The components of the mixed cereal-livestock farming system support each other (Haileslassie et al. 2005). Ehret (1979) reported that domestication of grasses was accompanied or even preceded by small ruminants (sheep and goat) husbandry, which indicate long standing history of the two sectors in Ethiopia. Livestock husbandry supports crop production mainly through providing traction power, while crop residue is used as a major livestock feed. Consequently, farmers keep wide variety and high livestock population. The livestock include cattle, small ruminants, equines, poultry and bees (ANRS-BFED, 2008). Small ruminants and cattle are the dominant animals accounting for 40% and 32% of the total population, respectively (Table 3.1).

Table 3.1 Livestock types in North and South Wello

Livestock type	Number of livestock		Total		
	North Wello	South Wello	Number	TLUs	%
Cattle	836,697	1,406,326	2,243,023	1,570,116	32.1
Sheep	798,128	1,998,539	2,796,667	279,667	40.0
Goats	594,596	810,432	1,405,028	140,503	20.1
Horses	21,246	31,050	52,296	41,837	0.7
Donkeys	169,478	288,532	458,010	229,005	6.5
Mules	10,896	21,467	32,363	22,654	0.5
Camels	10,576		10,576	10,576	0.2
Poultry	1,091,512	1,334,512	2,426,024	24	-
Bee colonies	52,738	105,155	157,893		-

Source: *Amhara National Regional State Bureau of Finance and Economic Development, 2006/2007 Budget year statistical bulletin.*

Livestock density in the North and South Wello zones is estimated to be about 76 tropical livestock units (TLUs) km^{-2}. The density is much higher than the recommendation for the humid tropics, which ranges between 19 and 42 TLUs km^{-2}

(Jahnke 1982). Thus, the recommended density for the study area is less than that of humid tropics, as it belongs to dry tropics. The high livestock density has led to over grazing. Livestock production is still traditional and productivity is low. Animal health, feed shortage and low productivity of the breeds are key problems of the sector, which directly or indirectly contribute to the resources degradation. However, the diversified livestock has helped farmers to withstand livestock loss due to health and other problems.

3.1.4 Natural resource base and management

In the effort to reverse the impact of land degradation, extensive soil and water conservation (SWC) measures have been carried out in the region as a whole and in Wello in particular. The DEM of the study area reveals that lands with slopes between 15% and 30% account for 28% of the total out of which a large proportion is used for cereal crop production. The area covered by farmland terraces accounts for only 11% of the total area (Table 3.2). A comparison of the area covered by the SWC interventions with the area that demands interventions based on slope indicates that still a lot has to be done. Information obtained from agriculture offices shows that construction of the SWC structures, maintenance operation and tree plantations require a large labor force, high financial investments and a great amount of material.

Table 3.2 Soil and water conservation interventions up to 2009

SWC intervention	North Wello	South Wello	Total
Cultivated land			
Farmland terrace (ha)	103377	215965	319342
Cutoff drains (km)	15088	25236	40324
Water way (km)	2969	77685	80654
Other structures (km)	38778		38778
Mountain and hillside protection			
Area closure (ha)	32620	91914	124534
Hillside terrace (ha)	1396119	81258	1477377
Other structures (No)	11452700	20939163	32391863
Gully treatment			
Check dam construction (km)	9329	151627	160956
Closed gullies (ha)	3913	153313	157226

Source: *North and South Wello Agriculture and Rural Development offices*

3.1.5 Demography

Wello is characterized by high population (Table 3.3). The population density of Wello (134 persons km^{-2}) is higher than the national average (84 persons km^{-2}) (Eyasu 2002; CSA 2008). The population of the Amhara region grew at an annual rate of 1.7% between 1994 and 2007, which is a lower rate than in the previous censuses. It was also almost 50% lower than the national growth rate. On the other hand, Wello has limitation of agriculturally suitable lands. Agricultural potential (≤ 15% slope) and marginally suitable land (15-30% slope) accounts for about 60%. Considering the area that can be used for most agricultural activities in relation to the population, the density is higher than the overall Ethiopian density and is estimated to be about 235 person km^{-2}.

Table 3.3 Human population of North and South Wello zones in 2007

	Urban		Rural		Urban + Rural		
Zone	Female	Male	Male	Female	Male	Female	Total
North Wello	55659	6060	678294	669330	754354	748929	1503283
South Wello	147164	155497	1101799	1114990	1248963	1270487	2519450
Total	302823	231557	1780093	1784320	2003317	2019416	4022733

Source: *CSA, 2008*.

In recent three decades, people have migrated from the zones due to both own and government initiatives. People from drought-affected northern parts of the country including Wello were taken to other parts such as Metekel, Metema, Beni-Shangul-Gumuz, Gambella and Kefa for resettlement. These resettlements continued sporadically until recent times. However, the recent resettlements have been on a voluntary basis where interested individuals moved to relatively open areas within the same region (Sørensen and Bekele 2009). Other forms of population outflow in the area are self-initiated short- and long-term migration to cities and towns for casual work. In most cases, temporary migration is by those who have some farmland, while long-term migration is mostly by the landless (Sonneveld and Keyzer 2003; Sørensen and Bekele 2009). The population outflow has reduced pressure on the land, which could slow further expansion of cultivation and grazing on marginal lands.

3.2 General methodology

The study evaluated the impact of SWC measures to maintain and/or rehabilitate degraded lands. Out of the different conservation measures, the role of farmland terrace and exclosure in maintaining or restoring soil fertility and crop yield was evaluated. In addition, LULC and NDVI change were used to track the rate and extent of land rehabilitation and/or degradation. Exclosure impact analysis was conducted in Gubalafto district in the North Wello zone, while evaluation of the impact of farmland terracing on soil fertility and crop yield was performed in Maybar watershed at the Maybar soil conservation research site (MSCRS) in the South Wello zone. The entire North and South Well zones were covered by the LULC and NDVI dynamics detection (Figure 3.6). The LULC and NDVI change analysis, and exclosure and farmland terracing impact evaluations were used to determine the role of SWC intervention on restoration of degraded lands. Moreover, the NDVI analysis was used to identify vegetation degradation hotspots.

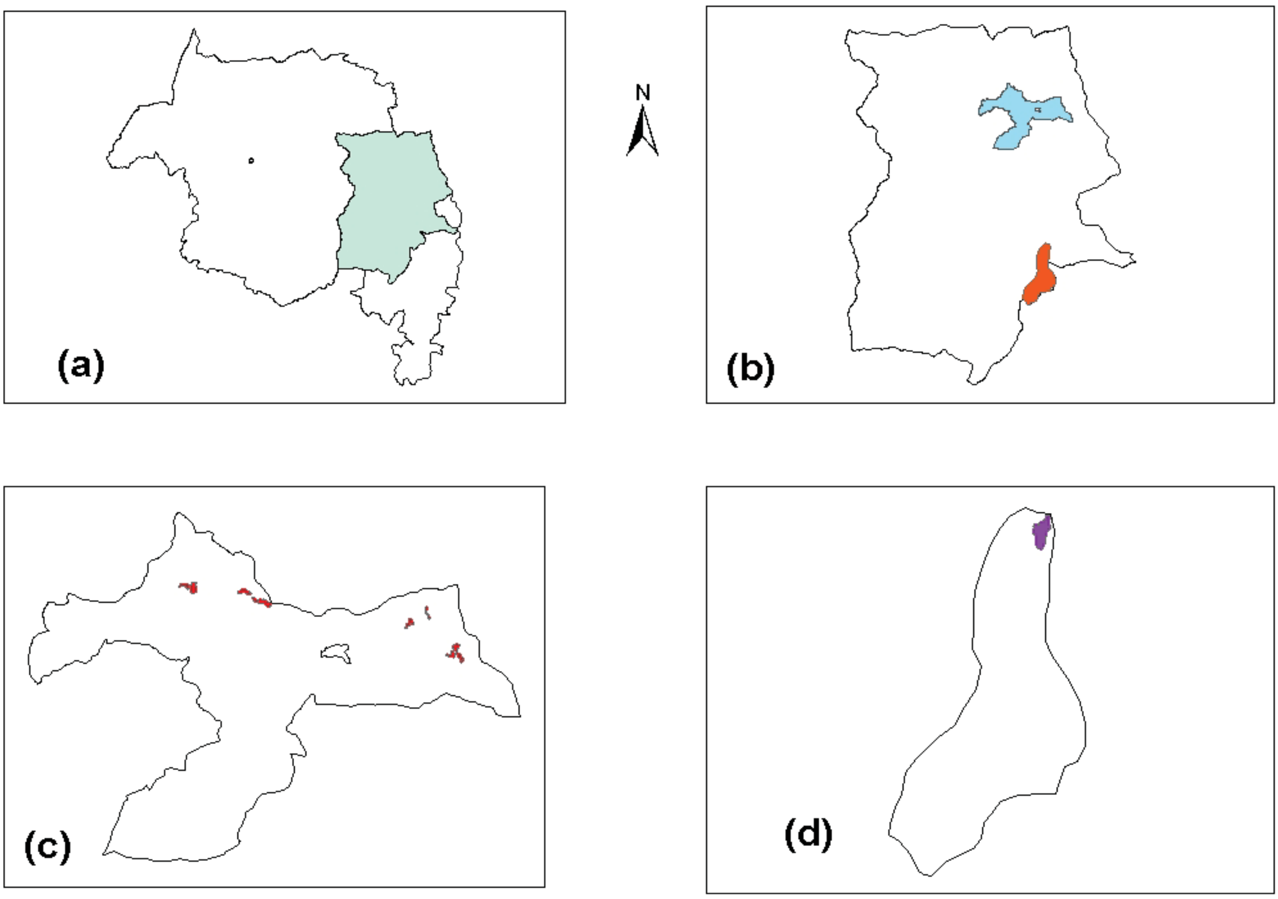


Figure 3.6 Location of sampling and study sites: (a) Wello in Amhara region, (b) Albuko and Gubalafto *Weredas* in Wello, (c) Exclosures sampling sites in Gubalafto *Wereda*, and d) Maybar watershed in Albuko *Wereda*

Land use-land cover and normalized difference vegetation index analysis

The main purpose of the analysis was to quantify the direction and extent of land use-land cover (LULC) and normalized difference vegetation index (NDVI) dynamics as indicators of land restoration resulting from SWC interventions. The LULC and NDVI dynamics analysis was done for the entire North and South Wello zones. The analysis used satellite data and ground-truth data. Ground-truth data collecting was supported by base maps that were developed using unsupervised classification of satellite data. Moderate resolution imaging spectrometer (MODIS) data with nearly 215,000 meter squier (463 m by 463 m pixel size) resolution were used. MODIS images and NDVI data between 2000 and 2010 were downloaded for free online. Out of all data sets, cloud-free images captured between January and March of each year were selected, and images of similar time used for the analysis. Details of image pre- and post-processing steps and classification results are discussed in Chapter 4. Similarly, in order to evaluate the depth and extent of land restoration due to the SWC and identify vegetation degradation hotspots, NDVI data of 2000 to 2010 were analyzed (Chapter 4).

Performance of farmland terracing in soil fertility and crop productivity

The role of farmland terrace in maintaining soil fertility was analyzed based on change in soil nutrient states and crop yield. The study was conducted in Lake Maybar watershed, particularly at the Maybar soil conservation research site (MSCRS). MSCRS is one of six soil conservation research sites in Ethiopia established in 1982. The project has constructed SWC structures, established baseline data and different setups such as field plots, and meteorological and river gauge stations. The project has been monitoring crop yield on fixed and non-fixed plots in both cropping seasons (*Belg* and *Kiremt*) since 1983. In this study, yield data collected by the project between 1995 and 2009 from fixed plots were utilized (Chapter 6). The MSCRS soil survey report conducted in 1983 (Weigel, 1986) was used as baseline to compare soil fertility change across terraces age. The MSCRS test plots were classified in different slopes and sampled at different terrace positions. The change in soil nutrients was evaluated by comparing the baseline and current survey result across space and time (Chapter 5).

Performance of exclosure in restoring soil fertility

The study was conducted in Gubalafto *Wereda* (district) considering exclosures of two different ages (10- and 27-year-old) and control (open grazing marginal land) located in two age-categorical zones (*Daga*/cool and *Weyna-Daga*/mild) at three landscape positions (lower, middle and upper) (Chapter 7). The identification of exclosures and control sites was done through intensive reconnaissance survey followed by sampling during the main survey. Soil samples were collected from each exclosure and control sites and analyzed for major soil properties. The soil analysis data were statistically tested using a general linear model.

Synthesizing implications of SWC measures for land rehabilitation

The results of the above four independent analyses were synthesized and the cumulative effects of land rehabilitation/restoration examined for the entire study area (Chapter 8). In this part, the LULC and NDVI change, crop yield and soil fertility change due to SWC interventions, mainly farmland terracing and exclosure, were evaluated in respect to land restoration. Based on the synthesis, concluding recommendations are given (Chapter 9).

4 LAND USE-LAND COVER AND NORMALIZED DIFFERENCE VEGETATION INDEX CHANGES IN WELLO

4.1 Introduction

The forest cover of the country in the early 1900´s was estimated about 40%. However, this was destroyed within half a century, i.e., the forest cover declined to 16% in the 1950´s and to 7% in the 1960´s (Pohjonen and Pukkala 1990; EFAP 1994; FAO 2001). Deforestation continued, and in 1980´s the forest cover had dropped to below 3% (Pohjonen and Pukkala 1990). Expansion of agricultural land at the expense of forest and natural vegetation, demand for household energy, forest fires due to extended dry periods and demand for timber and non-timber products were cited as leading causes of the forest cover deterioration (Pohjonen and Pukkala 1990; FAO 2001; Feoli et al. 2002). Among other factors, demand for cultivable and grazing land accounts for the larger share of the deforestation (Tefera et al. 2002; Asefa et al. 2003). This land use-land cover (LULC) change threatens the environment, resulting in accelerated soil erosion, habitat and biodiversity loss, micro-climatic change, and overall decline in the productivity of land (Badege 2001; Tefera et al. 2002; Asefa et al. 2003; Amsalu et al. 2007).

Intensified rehabilitation programs to reverse land degradation due to LULC change were widely launched after the 1984/85 drought (Badege 2001; Nyssen et al. 2004). Since then, various activities such as tree plantations at homesteads and in woodlots, reforestation and enclosure of degraded lands for self-regeneration (exclosure) have been carried out in most highland areas with special emphasis on drought-prone parts (Badege 2001; Mekuria et al. 2007). However, tree plantations are dominated by Eucalyptus species, while the cover of indigenous species continues to shrink (Pohjonen and Pukkala 1990). Though rehabilitation interventions showed improvements, the extent of those interventions did not offset the rate of conversion (Mekonnen and Bluffstone 2008). There are, however, no adequate studies that evaluate the performance of the various interventions, and some of the reports are not consistent. For example, FAO (2001) reported a 4.2% forest cover, while recently media has been broadcasting that the forest cover has increased to 11%.

The LULC change is clearly visible in degradation-prone areas of the northern highlands. Wello is one of the areas where natural resource rehabilitation interventions have been implemented in the past three decades. These include improvement of vegetation cover on marginal lands through exclosure, reforestation and tree planting. However, controversies exist on the spatial coverage and effectiveness of some interventions particularly concerning tree plantations. Although millions of tree seedlings have been planted every year, observers comment that forest cover is much below the reported plantings. Moreover, data on forest, woody vegetation and exclosure cover obtained from various levels of the government offices are inconsistent. This indicates existence of information and knowledge gaps on spatial and temporal LULC change due to the restoration measures. Therefore, the objective of this part of the study is to analyze LULC and normalized difference vegetation index (NDVI) change in space and time to assess the effectiveness of the conservation measures in reversing vegetation degradation thereby land degradation in Wello, northern Ethiopia, and using MODIS satellite data.

4.2 Materials and methods

4.2.1 Study area

The study was conducted in the North and South Wello zones of the Amhara National Regional State, which is located between 10°12' and 12°22' north latitude and 38°30' and 40°14' east longitude. The study area covers a total of 30,000 km^2. The two zones have similar socio-economic and biophysical characteristics such as geology, geomorphology, soils, climate, agricultural practices, and vegetation cover (FAO 1984; Tefera et al. 1996). See Chapter 3 for the overall description of the study area.

4.2.2 MODIS data acquisition and preparation

In order to understand the impact of soil and water conservation (SWC) interventions, particularly the biological measures of land restoration, LULC and inter-annual normalized difference vegetation index (NDVI) changes were analyzed using moderate resolution imaging spectrometer (MODIS) data. NDVI is a standardized index to measure greenness. The MODIS surface reflectance image is available for free online on ftp://e4ftl01.cr.usgs.gov/MOLT/MOD09A1. MODIS surface reflectance image data are composited every 8 days and delivered in approximately 10-degree blocks in sinusoidal grid mapping projection. The MOD09A1 terra in 215,000 m^2 resolution sin grid V005 for 2000 and 2009 were downloaded for the study. The data are available in hierarchical data format (HDF) processed by MODIS re-projection tool (MRT) into Geo TIFF data. The extracted data are single integer pixel type, which has 13 bands in 16-bit pixel depth. To reduce impacts due to differences in the time of data acquisition, images captured between January and March were found appropriate for this analysis because in this period the study area has a clear sky (more or less cloud free) and crops have already been harvested. The time after crop harvest was preferred to avoid the effect of sorghum and maize signatures, which may be confused with bushes and shrubs (Hill and Donald 2003). Finally, images captured in March 2000 and 2009 were selected and used for the analysis. Relevant pre-processing such as re-projection and geometric correction were performed to prepare the images for further analysis.

NDVI data is calculated from satellite imagery as NDVI = (NIR – RED)/(NIR + RED), where NIR is reflectivity of plant materials in the near-infrared and RED is the chlorophyll pigment absorption in the red band (Lillesand 2004). However, like MODIS imagery, NDVI data of same resolution (250 m) is available for free online on ftp://e4ftl01.cr.usgs.gov/MOLT/MOD13A1. NDVI data are delivered in the same degree blocks and projection as the MODIS surface reflectance image except that they were composited only twice a month. NDVI data of the non-growing period that covers the period between January and April from 2000 to 2010 were acquired. The NDVI values between January and April for each year were averaged. Finally, the averaged data were compared spatially and temporally. The analysis used linear relationships of year (X) and NDVI (Y) to determine inter-annual change using ArcGIS adopted from Vlek et al. (2008).

The model is given as:

$$Y = AX + B + \varepsilon \qquad (4.1)$$

where A = slope, B = intercept, ε = random error

Xi = dry months (January to April): one output for each year, i = 2000 to 2010,

Yi = mean NDVI values of the dry period (January to April) for each year, i = 2000 to 2010

NDVI slope (calculated slope [A_{cal}] = A) was statistically tested using t-test in such a way that: If $|t_o| \geq t_P$, df: then the calculated slope coefficient is significantly different from zero. Therefore, NDVI slope was tested for significance at 75%, 90% and 95%

confidences level, at the degree of freedom (df), n-2 = 11-2 = 9 and n = number of years.

- If $|t_o| \geq t_{0.25,9} = 0.703$, then A_{cal} is significantly different from zero at 75% confidence level
- If $|t_o| \geq t_{0.10,9} = 1.383$, then A_{cal} is significantly different from zero at 90% confidence level
- If $|t_o| \geq t_{0.05,9} = 1.833$, then A_{cal} is significantly different from zero at 95% confidence level

4.2.3 Ground truth data collection and LULC type identification

In order to support image classification, ground truthing was done in two phases. First, reconnaissance assessment was done during the research site identification. The reconnaissance survey aimed to gain general information of the study area and existing biophysical conditions. In this phase, an unsupervised classification-based LULC map was used, and signatures of the major land uses were interpreted in the field. After the reconnaissance survey, tentative LULC types were defined. During the main field survey, the coordinates of the ground control points (GCPs) of the past and actual LULC types were collected using a global positioning system (GPS). The GCPs for the LULC of 2000 were collected based on information from elderly people and agriculture offices. A total of 250 GCPs were collected for each year through field survey and secondary information. In most cases, GCPs of the year 2000 and 2009 were the same except in cases where the respondents were not certain of the year 2000 changes.

Before the reconnaissance survey**,** the LULC of the study area was mapped in twelve mapping units using unsupervised classification. After the main survey, the final land use/cover classification was done by maximum likelihood supervised classification using the training areas identified during the field survey. Due to the coarse resolution of the satellite images and low separability of the signatures, the LULC classes were reduced to five by aggregating some classes together. Cultivated land, settlements and bare land have very similar signatures with low separability. Thus, these classes were clustered to the same mapping unit. Similarly, forests and woodlands were aggregated as forestland. In the early period, exclosures are dominated by newly emerging grasses with little regenerating woody vegetation and have a similar signature to that of grasslands. Thus, grasslands and woody grassland were classified as grassland/woody grassland. Accordingly, the LULC types were grouped in five major classes: i) cultivated land/others, ii) forest, iii) degraded woody vegetation, iv) grasslands/woody grasslands, and v) water bodies (Table 4.1).

Table 4.1 Description of LULC types

No.	LULC type	Description
(i)	Cultivated lands/others	Includes wide range of LULC, mainly cultivated lands (irrigated and non-irrigated), settlements up to city level and bare lands.
(ii)	Forest	Represents area covered by woody vegetation with more than 20% canopy cover. This includes forests, woodlands, old exclosures and bush lands.
(iii)	Degraded woody vegetation	Area with woody remnants and some scattered woody vegetation where the canopy and ground cover were less than 5% and 25%, respectively. These lands are used for free livestock grazing and have free access for firewood and construction wood collection.
(iv)	Grasslands/woody grassland	Includes grasslands and woody grassland. New exclosures were at first degraded woody vegetation, but due to exclusion from human and animal intervention the areas started to regenerate. Thus, the ground cover improved (> 25%), but the canopy cover is still low, between 5% and 20%. After two to three years of exclosure, the ground is largely covered by grasses, scrubs and shrubs.
(v)	Water bodies	Includes lakes (Hayk, Hardibo and Maybahr), swamps (Hara Swamp), ponds and water accumulated at some points within wide river courses.

4.2.4 Digital elevation model

In order to compare the LULC and NDVI change against land-use policy, which is based on slope, the study area was classified into slope classes using a 30-m resolution gridded elevation data in digital elevation model (DEM). The land-use policy demarcated land use based on three slope classes, i.e., less than 30%, 30% to 60% and over 60% slopes. The policy determined land use as i) land allowed for cultivation and grazing, ii) land where perennial crops such as fruits, coffee and others annual crop cultivation is allowed, and iii) land where cultivation and grazing are prohibited in the above mentioned slope ranges (Anonymous 2005; 2006). The policy urges appropriate management interventions in all land use/cover types so that sustainable use is assured without compromising the advantage of upcoming generations.

4.3 Results and discussion

4.3.1 Implication of the topography on LULC change

The DEM shows that about 60% of the study area has <30% slope, about 30% of the area has slopes 30% to 60%, and about 10% has slopes >60% (Figure 4.1). This means that nearly 40% of the study area falls within the steep slope category where cultivation should not be allowed without proper conservation strategies. According to rural land administration and use policy (Anonymous, 2005; 2006), the area coverage of the land that is allowed for cultivation (land with a slope <30%) accounts for nearly 60% of the total area. Although this area seems quite large, these lands include the area covered by rock outcropping and very shallow soils. Generally, the DEM analysis reveals that dissection and fragmentation increased with slope increase, which indicates severe soil erosion and thereby indicates the importance of SWC measures with slope increase.

Understanding the topographic setup of an area is important for implementing appropriate land-use plans (Woldesemait 1983). It is important to indicate that other limiting factors such as soil depth, rock outcropping and climatic factors also determine the potential of the land with slopes <30%. For example, in the areas with slopes below 30% on the cold (*Wurch*) highland plateaus (e.g., Kebero-Meda and Guguftu) crop production is restricted by cool temperatures in the main rainy (*Kiremt*) season and failure of spring (*Belg*) rainfall. Due to slope limitation, the policy restricts land between 30% and 60% slope to be used for annual crops. But practically in the study area with slopes over 30% is generally used for cereal crop production. On the other hand, the population of the study area is still increasing, which means that there is a need for solutions and alternative livelihood options. The DEM analysis demonstrates the need of conservation measures, while the population growth rate and the limited livelihood options signal a need of more agricultural lands. Therefore, proper land use planning based on the knowledge of the current situation is necessary to minimize interest conflicts between environment and livelihood options.

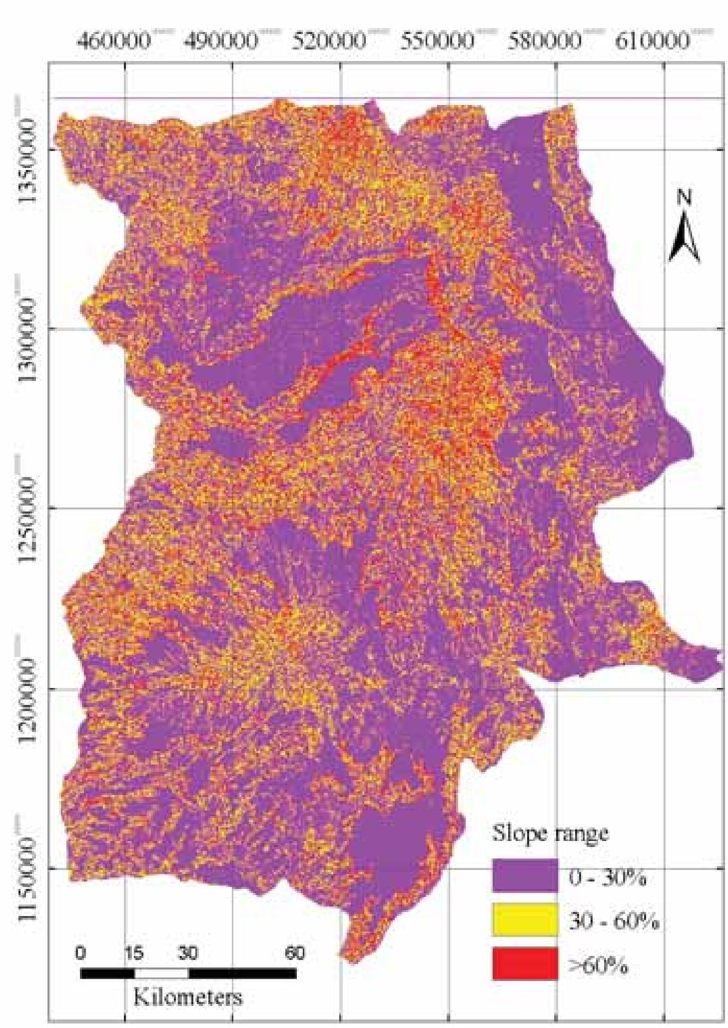


Figure 4.1 DEM of North and South Wello Zones showing slope range

4.3.2 LULC dynamics of Wello area

The analysis of the 2000 and 2009 MODIS data reveals considerable LULC change as a response to the vegetation restoration interventions. Accuracy assessment revealed 79.2% and 76.0% accuracy for the 2000 and 2009 image classification, respectively (Table 4.2). In the error matrix (Table 4.2), bolded diagonal numbers are counts of correctly classified pixels, while the off-diagonal numbers indicate counts of misclassified pixels. The off-diagonal numbers in the columns and rows are number of pixels commissioned to or omitted from particular LULC types. The LULC change in the current study shows remarkable variation in the different LULC types. Degraded woody vegetation and woody grasslands showed high dynamics (Figure 4.2 and Table 4.3). The area of degraded woody vegetation in 2000 accounted for about 19.7%, whereas in 2009 it decreased to 6.7% (Table 4.3). On the other hand, grasslands/woody grasslands increased from 10.8% in 2000 to 25.4% in 2009. The other LULC changes were small. For example, the area covered by cultivated/other land uses decreased by less than 1%, forest cover by 0.7 %, and there was negligible change in water bodies. The major water bodies in the study area are lakes that have small watersheds, (namely Hayk, Hardibo and Maybar).

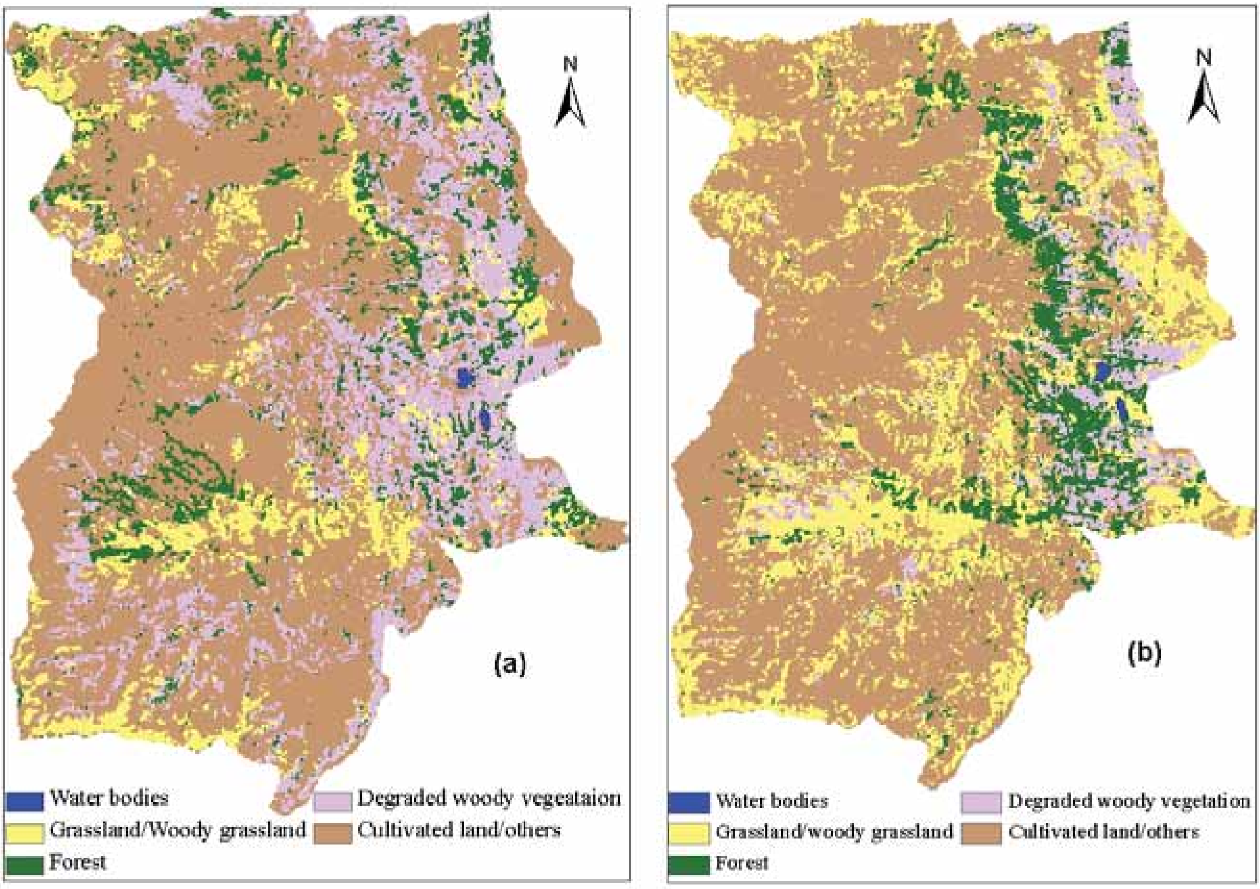


Figure 4.2 Land use/land cover of Wello in: (a) 2000 and (b) 2009

Table 4.2 Classification accuracy error matrix based on pixel by pixel comparison

a) LULC change of 2000, overall accuracy 79.2% and overall Kappa Statistics of 0.7158

	Reference data						**Accuracy**		Kappa
LULC types	Cultivated land/others	Forest	Degraded woody vegetation	Grassland/ woody grassland	Water bodies	Row total	Product	User	(K^) statistics
Cultivated land/others	**82**	0	3	2	0	87	72.57	94.25	0.8067
Forest	5	**51**	3	0	1	60	91.07	85.00	0.8067
Degraded woody vegetation	18	3	**35**	1	2	59	77.78	59.32	0.5039
Grassland/woody grassland	8	2	4	**20**	0	34	86.96	58.82	0.5465
Water bodies	0	0	0	0	**10**	10	76.92	100	1.0000
Column total	113	56	45	23	13	250			

b) LULC change of 2009, overall accuracy 76.0% and overall Kappa Statistics of 0.6733

	Reference data						**Accuracy**		Kappa
LULC types	Cultivated land/others	Forest	Degraded woody vegetation	Grassland/ woody grassland	Water bodies	Row total	Product	User	(K^) statistics
Cultivated land/other	**66**	1	3	7	1	78	80.30	82.81	0.7665
Forest	2	**53**	2	6	1	64	61.90	81.25	0.7953
Degraded woody vegetation	0	3	**13**	0	0	16	73.33	84.62	0.7596
Grassland/woody grassland	22	9	3	**47**	0	81	78.33	58.02	0.4477
Water bodies	0	0	0	0	**11**	11	84.62	100.00	1.0000
Column total	90	66	21	60	13	250			

Table 4.3 LULC dynamics of North and South Wello zones

LULC classes	LULC in 2000 Ha	%	LULC in 2009 Ha	%	Change 2009-2000
Cultivated land/others	1787300	59.6	1758800	58.6	-0.9
Forest	295600	9.8	274400	9.1	-0.7
Degraded woody vegetation	590900	19.7	202000	6.7	-13.0
Grassland/woody grassland	323100	10.8	761500	25.4	14.6
Water bodies	3900	0.13	3800	0.13	nil
Total	3000800	100	3000500	100	

Note: *The slight difference between the two totals (300 ha) is area estimation rounding error incurred by the software (ArcGIS) and due to rounding of the output. But the error is too small to change the analysis result.*

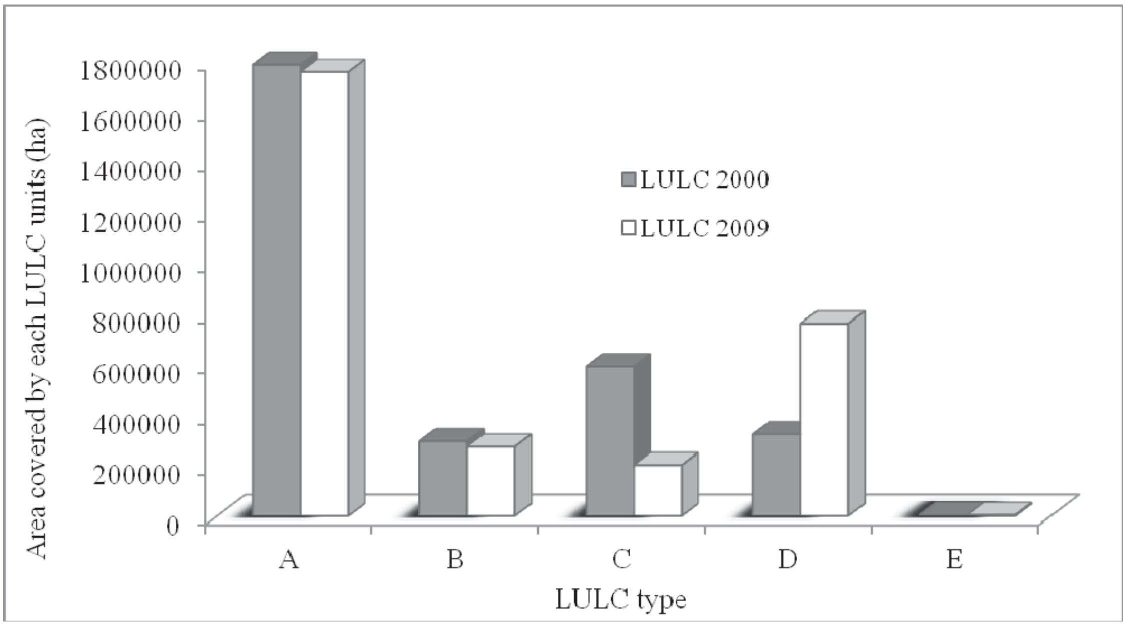
The LULC dynamics of the area depicted spatio-temporal variability. For example, forest cover change showed remarkable spatial variability (Figure 4.2). Although steep lands (mountains, gorges and hills) are distributed over the entire area, there were considerable improvements in the eastern escarpment. On the other hand, scattered groves and thin strips of forest depicted on the 2000 image in the northeast, southeast and central part of the study area were fully or partly destroyed by 2009 images. The forests occupied steep slopes along river courses and mountainsides. Generally, forests/vegetation showed improvement in density and area coverage on the eastern escarpments and mountains. The forest cover improvements were observed in areas where their coverage was originally better and conservation had been practiced regardless of topographic similarity between the different parts. However, rate and extent of forest cover change was very small as compared to the land lacking vegetation cover.

On the other hand, considerable grassland/woody grassland cover changes indicate achievement of restoration interventions. The woody grassland represents new exclosures undergoing rehabilitation. At an early age, exclosures are dominated by non-woody vegetation such as scrubs, herbs and grasses (Descheemaerker et al. 2006; Kalinina et al. 2009; Mekuria et al. 2011). As a result, the signature is similar to that of grassland. Vegetation succession on degraded land after exclosure followed the order of non woody vegetation (grasses, herbaceous plants and shrubs), woody grassland, mixed trees and forests dominated by limited tree species (Figure 4.3). The vegetation restoration pattern on degraded land following exclosure resembles that reported by Kalinina et al. (2009) and Descheemaerker et al. (2006). Newly established exclosures show considerably improved vegetation cover on steep landscapes within a few years time.

Figure 4.3 Exclosure vegetation change across time: (a) 10 years old (woody grassland), and (b) 27 years old (forest)

The DEM-generated slope map reveals that about 10% of the land has slopes of over 60%. Forest cover in the study area accounts for nearly 9% (Table 4.3 and Figure 4.4). The field observations also verified that very steep slopes, except rocky areas, were largely covered by forest. It was also observed that old exclosures developed to forest with over 60% canopy cover (Figure 4.3 b). The comparison of slopes, LULC maps and field observations showed that the forest occupied very steep landscapes.

Nonetheless, vegetation restoration and succession depend on site-specific bio-physical and climatic conditions such as soil seed reserve, soil depth, rockiness, rainfall and temperature (Carla et al. 2003; Descheemaeker et al. 2006; Oba et al. 2006). Carla et al. (2003) also reported that restoration is inversely related to degradation. Generally, the slope and LULC maps indicate that very steep landscape (slope >60%) were dominantly covered by forest, while woody grassland occupied steep landscape (slopes 30% to 60%). Woody grassland was observed on new exclosures that were undergoing succession from degraded vegetation remnants to forest. The time interval in which degraded lands develop to forest through self-restoration due to exclosure depends on climatic conditions and bio-physical potential of the area (Descheemaerker et al. 2006).



Note: Land-use/land-cover, i.e., A = cultivated and others, B = forest, C = degraded woody vegetation, D = grassland/woody grassland and E = water bodies

Figure 4.4 Land use/land cover dynamics of Wello

The analysis indicates that the area covered by grassland/woody grassland increased by 14.4% from 2000 to 2009 (Figure 4.4) due to the effort to restore degraded lands. Although grassland and woody grassland were aggregated together in one LULC mapping unit, they occupy different topographic setups. Most grassland occupies low-lying areas that have drainage problems as they are prone to water-logging during rainy seasons. This makes these lands unsuitable for other uses like cultivation, so they have remained as pasture for centuries. Conversely, woody grasslands are mostly recent exclosures that occupy steep landscapes (mainly over 30% slopes). This indicates that the major change on grassland/woody grassland is mainly due to recent exclosure. The area mapped as grassland/woody grassland on steep slopes has undergone various changes. These areas originally had a forest cover before clearance. The current restoration measures (exclosure) have led to regeneration of the forest. Observation of exclosures of different age indicates that woody grasslands will develop to forest or bush land through time as the lower-order vegetation is replaced by higher order. Similar vegetation dynamics with age of exclosure were reported by different studies (Carla et al. 2003; Descheemaerker et al. 2006; Zhao et al. 2010; Mekuria et al. 2011).

According to the 2009 image, the area covered by forest and grasslands/woody grassland accounts for 34.5%, where the area above 30% slope accounts for 40% of the total area. Grassland/woody grassland in 2000 accounted for 10.8%, which indicates that the area of grasslands located on slopes <30% was smaller than 10.8%. Thus, steep slope lands that require restoration through exclosure were considerably covered. Conversely, cultivated land/other LULC types showed non-significant change.

The rural land-use policy allows annual crop cultivation on lands with slopes <30%, and these areas account for 60% of the total study area. Here, a considerable area of the less steep (<30% slopes) lands are not under cultivation due to various limitations and competition with other uses, such as settlements and space for infrastructure development. Due to the population growth, the demand for land for settlements and infrastructure has increased. As a result, rural settlements, towns, cities and public infrastructures like roads, schools and health institutions have been expanding on lands that were used for cultivation and grazing. Moreover, considerable areas have also been taken out of cultivation due to other limitations such as shallow soil depths and rock outcroppings. Other LULC types such as water bodies, grasslands and drainage courses are also found on flatter land (<30% slope). In order to reduce flood hazards at the down-slope positions and further degradation on steep landscapes, the regional government also moved farmers from steep land to down-slope positions. The above factors have led to a shrinking area of cultivable lands. At the study scale, separation of cultivated land from other LULC types was difficult due to low separability of the signatures. This created difficulty to account the components of land use within each mapping unit. However, from the above explanation, it can be deduced that the area of cultivable land has been decreasing while the population has been growing. Generally, the potential to extend cultivable land or to convert non-agricultural land to cultivation has apparently already exceeded the maximum limit.

4.3.3 Spatio-temporal NDVI changes and implications for restoration

NDVI time-serious data can be used to generate information about vegetation phenology and cover (Hill and Donland 2003). Like the LULC change, the NDVI analysis showed vegetation cover spatial and temporal variability. Higher mean NDVI of the dry seasons (January to April) was observed in the eastern parts, and intermediate and lower dynamics in the central and western parts, respectively (Figure 4.5).

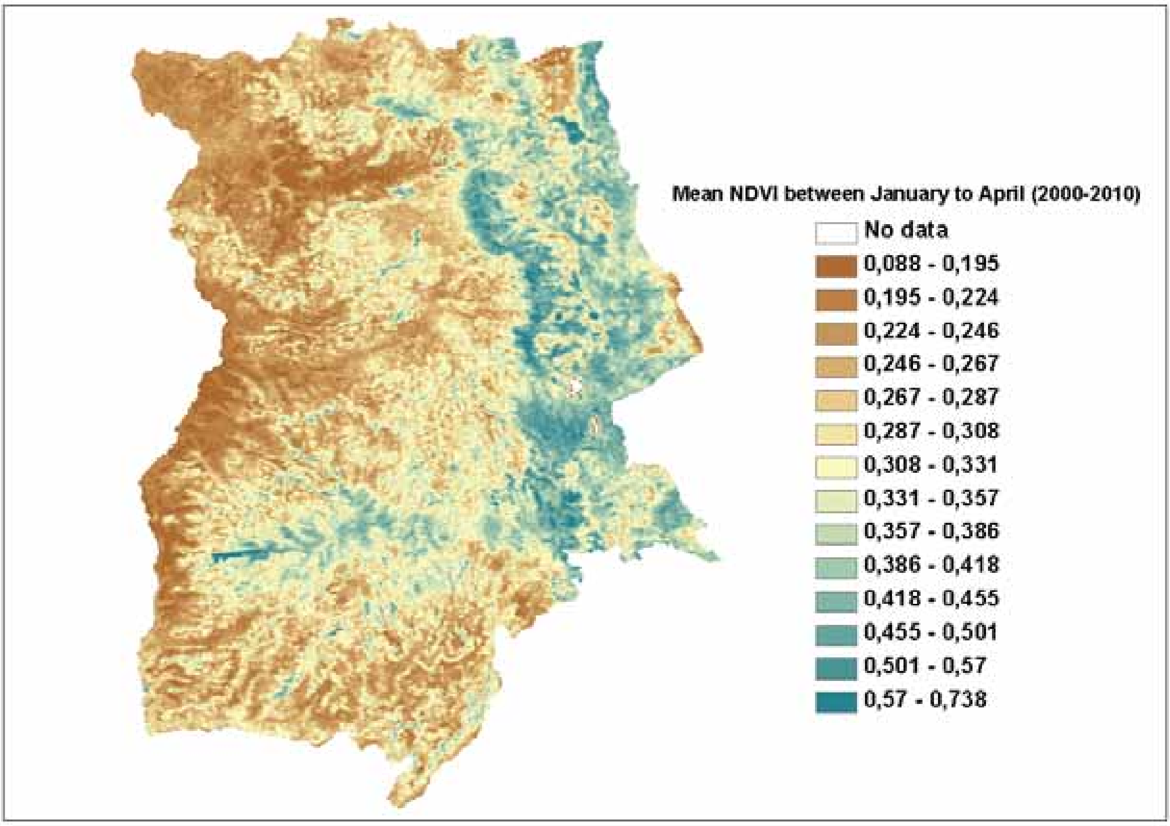
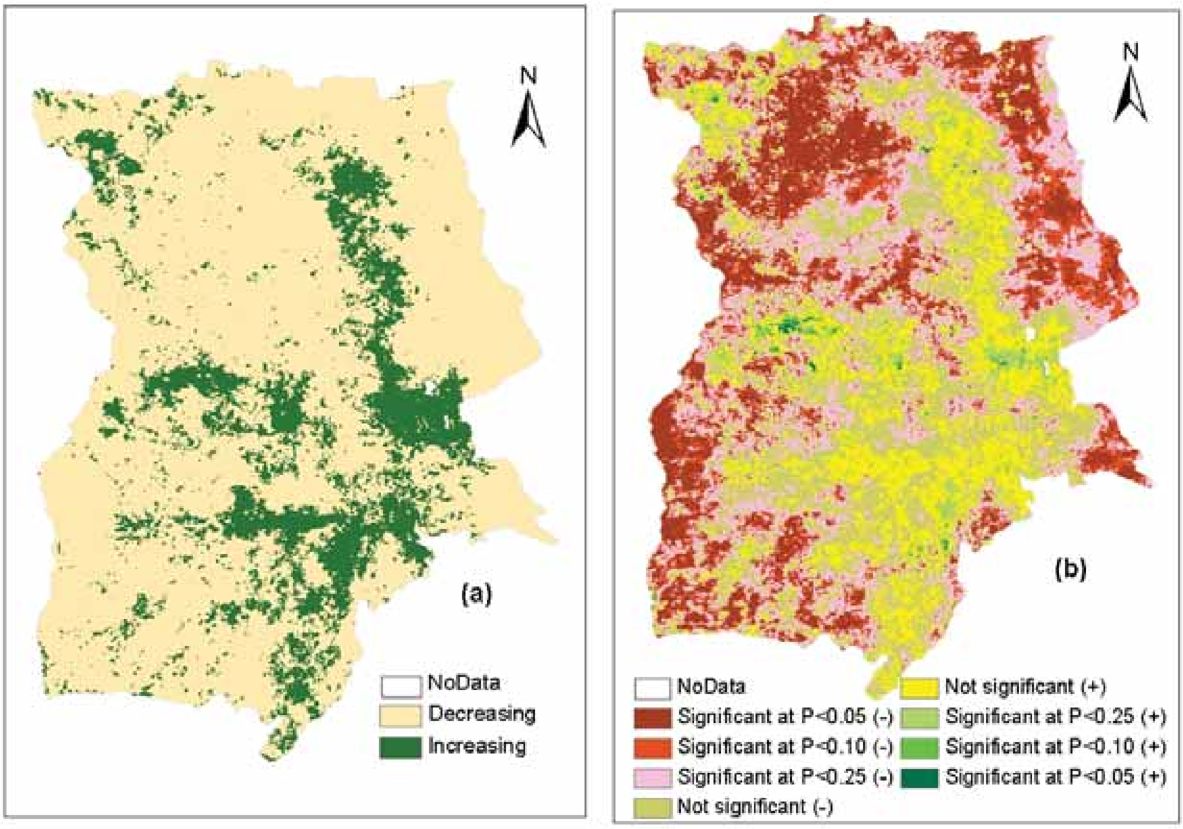


Figure 4.5 Mean NDVI values in dry periods (January to April) 2000 to 2010

The analysis was simplified by visualizing NDVI values with increasing and decreasing values in two colors (Figure 4.6a). Similar to the mean values, the temporal NDVI change over time showed an increasing trend in some parts, while larger areas showed a declining trend (Figure 4.6a). The statistical analysis (t-test) revealed that temporal NDVI slope changes were predominantly insignificant, while some areas showed significant differences at P = 0.05 and 0.1 (Figure 4.6b). Areas showing significant inter-annual NDVI change could have shown difference at higher probability level, if the analysis was done since the period exclosure practice has been started in the area. However, due to lack of data (MODIS NDVI data is available since 2000) the analysis covered the period after 2000.



Note: (-) show decreasing and (+) increasing trend

Figure 4.6 NDVI changes between 2000 and 2010 (January to April): (a) crude NDVI change, and (b) NDVI change by significant level

In order to identify the area showing vegetation decline or improvement as proxy indicator of restoration and/or degradation, spatio-temporal NDVI changes were further analyzed. The analysis indicates that the vegetation signature particularly in the central, central east and southeastern area showed an increasing trend, while the eastern, northwestern and southwestern parts showed a declining trend (Figure 4.6b). In relative terms, areas showing a significant NDVI decline (P = 0.05) cover a considerably larger area as compared to areas showing a significant (P = 0.05) NDVI improvement. Areas with non-significant NDVI (slight decline and gain) cover a larger proportion of the study area of which areas showing a declining trend are larger (Figure 4.6b). Higher NDVI values, which help to identify the state of the perennial vegetation remaining green throughout the year, could indicate vegetation degradation or restoration. This holds true where vegetation is not dominated by species with shading leaves in dry periods. In the study area, annual vegetation of the highlands is dominated by evergreen species, while the midlands and lowlands are dominated by acacia species that flourish during the dry period. This indicates that the analysis is unlikely influenced by vegetation types. Therefore, areas showing significant restoration are very small both at the 90% and 95% confidence level. This comparison is similar to that of the LULC change analysis where the wood vegetation cover showed little change.

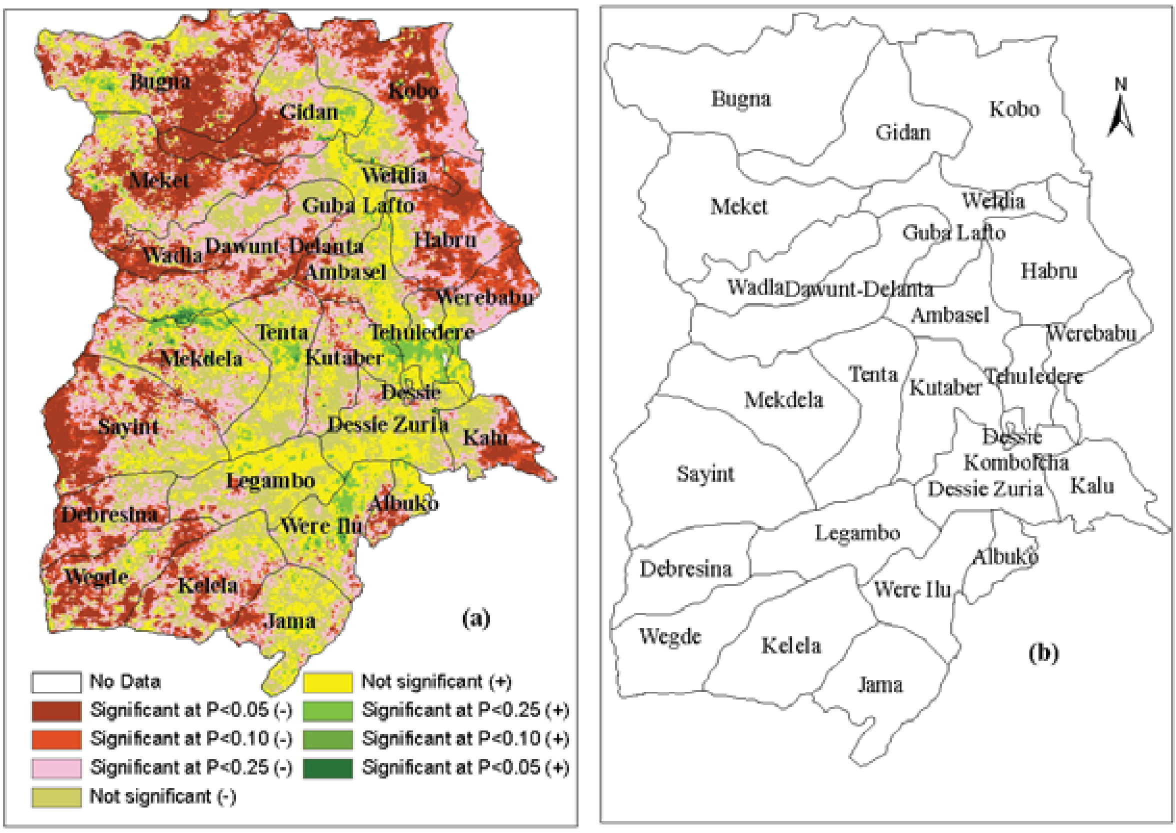


Figure 4.7 Inter-annual NDVI change: (a) NDVI gradients across districts, (b) districts in the study area

Comparison of the DEM slope map (Figure 4.1) and NDVI change map (Figure 4.6b) reveals that vegetation degradation hotspots occupied relatively gently sloped areas, while areas showing restoration mainly occupied steeper slopes. The inter-annual NDVI change was also clearly different depending on administrative unit (Figure 4.7). Although NDVI changes showed differences across districts, areas showing significant vegetation restoration and degradation occupy nearly adjacent areas. In relative terms, the northeast, western and northwest central parts (Figure 4.7) were identified as hotspot areas of vegetation degradation. Accordingly, most of Kobo, eastern Bugna, southwestern and northern Gidan, larger parts of Meket and Habru, western Wadela and parts of Dawunt-Delanta in North Wello; and eastern Kalu, southern Albuko, southern Kelela, large parts of Debresina, Wegde and Werebabu, a few parts of Sayint districts in South Wello are the hotspot areas (Figure 4.7 and Table 4.4). In contrast, large parts of Ambasel, Dessie-Zuria, Guba-Lafto, Jama, Legambo, Tehuledere, Tenta and Were-Illu, some parts of western Bugna, southeast Gidan, and parts of Mekdla districts showed restoration. Generally, areas showing restoration followed regular geographic patterns mainly along highways, while hotspot areas are dominantly located in remote parts.

Table 4.4 NDVI change between 2000 and 2010 (January to April) by district

Districts in South Wello Zone	NDVI trend A	NDVI trend B	Districts in North Wello Zone	NDVI trend A	NDVI trend B
Albuko	✓	✓	Bugna	✓	
Ambasel	✓	✓	Dawunt-Delanta	✓	
Debresina	✓		Gidan	✓	✓
Dessie Zuria	✓	✓	Kobo	✓	
Jama	✓	✓	Meket	✓	
Kalu	✓		Wadla	✓	
Kelela	✓		Guba-Lafto		✓
Kombolcha	✓				
Kutaber	✓				
Legambo		✓			
Mekdela	✓	✓			
Sayint	✓				
Habru	✓				
Tehuledere	✓	✓			
Tenta	✓	✓			
Wegde	✓				
Were-Ilu	✓	✓			
Werebabu	✓				

Note: *A = NDVI decline with some increase, B = NDVI increase with some decrease*

Comparison of the NDVI trend considering 2000, 2005 and 2010 showed improvement across time. The areas covered by higher NDVI values in 2000 were scattered and sparse, while in 2005 and 2010 increased both in depth and width (Figure 4.8). The area covered by higher NDVI values (> 0.4) increased from 3.6% in 2000 to 14.3% in 2005 and to 16.1% in 2010. The area covered NDVI values between 0.3 and 0.4, which might be new exclosure (grassland/woody grassland) increased from 27.6% in 2000 to 30% in 2010 (Table 4.5). This shows that the green biomass cover and signal depth showed a considerable change over time. This analysis is also similar to the results of the LULC change detection.

Table 4.5 NDVI change with respect to area cover (ha) in selected years

NDVI	Area coverage (ha and %) by NDVI values across the year					
	Year 2000		Year 2005		Year 2010	
	ha	%	ha	%	ha	%
0-0.1	1000	0.04	900	0.03	1400	0.05
0.1-0.2	108800	3.77	144900	5.02	149200	5.17
0.2-0-3	1874300	64.99	1403800	48.67	1408900	48.83
0.3-0.4	797300	27.64	922700	31.99	861400	29.85
0.4-0.5	88200	3.06	317800	11.02	338500	11.73
0.5-0.6	11800	0.41	81100	2.81	111900	3.88
>0.6	2700	0.09	13400	0.46	14200	0.49

The analysis also reveals that the study area has been subject to remarkable vegetation dynamics. The change was observed in areas where few vegetation signatures had previously been detected. The major restoration measures in the area are protection of degraded lands by self-regeneration, which is termed as exclosure. As evidenced through NDVI analysis and field visits, the exclosure practiced in recent times has brought tangible change. Areas showing positive but non-significant NDVI change represent recent exclosures, which are dominated by lower-layer vegetation such as grasses, herbaceous and scattered woody vegetation; signals are similar to that of grasslands and dried during the analysis periods, i.e., January to April. Therefore, the NDVI values smaller than the green vegetation in the study months represent dry grasses in recent exclosures. This implies that the area has been undergoing tangible vegetation restoration in some parts that will develop to higher vegetation layers through time. On the other hand, the decreased vegetation cover in the other parts could be due to less conservation activities of the community and local administration. Areas where SWC interventions started earlier showed considerable improvement. Intervention of NGOs in natural resources management (NRM) stimulated and enhanced the activities of the community and local level offices (Tekle 1999; Descheemaerker et al. 2006). Informants interviewed during the field research acknowledged the SWC effort of government and non-government organizations such as the respective districts agriculture offices, Organization for Rehabilitation and Development in Amhara (ORDA), Kobo-Girana Valley Development Program (KGVDP), Ethiopian Orthodox Church Development and Inter-Church Aid Commission (EOC-DICAC) and Ethiopian Evangelical Church Mekane Yesus Development and Social Services Commission (EECMY-DASSC).

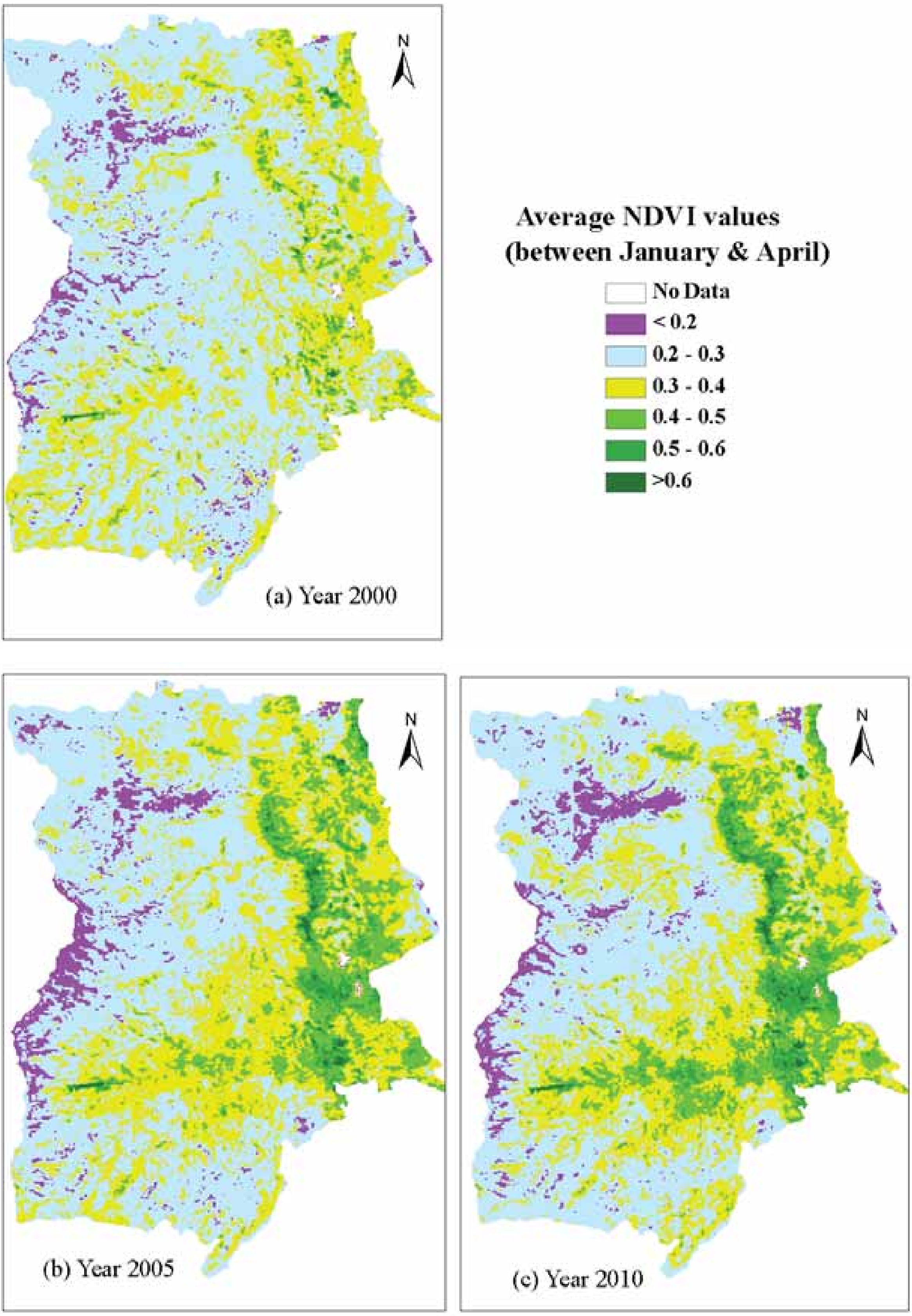


Figure 4.8 NDVI spatio-temporal variation in response to restoration

The field survey revealed that the study area has been severely affected by both *in-situ* and *offsite* land degradation impacts. As indicated on the DEM, 40% of the study area is steep to very steep (>30%). Steep-slope landscapes are non-resilient to LULC change. As a result, any inappropriate change immediately and permanently impacts the environment negatively.

People explained the severity of the problem by comparing the current river flow with that of some years ago. Elderly people witnessed that some decades ago rivers were not as wide as today (Figure 4.9a) and most now flow throughout the year and have ample water. In peak rainy seasons, rivers did not use to carry stones and boulders. In recent decades, during the main rainy seasons (July to September), rivers become full just after peak rains, while in the dry seasons rivers discharge reduces critically and in some cases completely dry. The field survey also indicated that gently sloping lands and valley plains are severely affected by expanding river courses, by land dissection by gullies, and by landslides and all forms of soil erosion (Figure 4.9a). Rivers are expanding on agriculturally potential lands located in valley plains. Land degradation due to river course erosion is not only encroaching on agricultural land but is also creating problems for the traditional irrigation system and threatening accessibility. Traditionally, farmers use earthen irrigation diversions. However, the degradation hampers the practices as the rivers are becoming wide and deep. Moreover, rivers and streams occasionally change direction, consequently damaging farmlands. It is also observed that due to the river and stream route changes, agricultural lands have been destroyed by gravel, stone and boulder deposition.

The SWC measures implemented have led to tangible changes in the environment. A clear difference can be observed between areas with and without conservation measures (Figure 4.9). People living around the protected area clearly perceive the advantages. Vegetation cover, bio-diversity and soil fertility restoration and improved forage production are some of *in-situ* advantages of the conservation. The various offsite advantages of SWC such as exclosure include improvement of downstream hydrology, and decrease in flood risk and riverbank erosion. However, to fully halt the impact of degradation, long-term efforts and large investments are necessary.

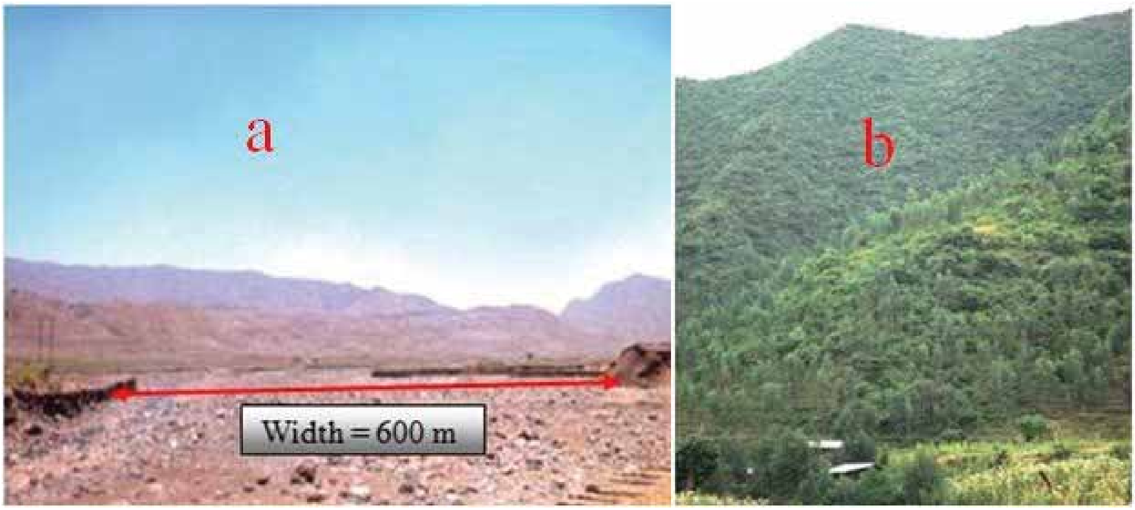


Figure 4.9 Contrast between (a) degraded and (b) rehabilitated environment

4.3.4 Possible drivers of LULC change in Wello

Population growth and LULC changes

Agricultural land demand and the need to increase production through shifting cultivation in order to meet the growing population food demand was a major push factor of the LULC change in the Ethiopian highlands (Amsalu et al. 2007). Elderly people mentioned that shifting cultivation, locally termed as *Mofer Zemet Ersha*, was practiced for a long period in order to maintain soil fertility and crop production. Shifting cultivation and expansion of cultivation and grazing took place at the expense of forest lands (Badege 2001; Amsalu et al. 2007). Conversion of forest lands to cultivation and grazing in the Ethiopian highlands took place on favorable land. The practice still continues on steep landscapes as land becomes limited. The same applies to expansion of cultivation and grazing onto marginal land, which has aggressively continued until recent (Tekle 1999; Amsalu et al. 2007).

Population growth has been cited as the major push factor of the LULC change, which in turn results in severe degradation in most northern highlands. A highland reclamation study (FAO 1986) identified the population-pressure-driven LULC as the major cause of land degradation. The studies indicated that expansion of agricultural land already passed the maximum limit for agricultural use, i.e., cultivation and grazing has exhausted marginal lands (Tekle 1999; Badege 2001; Tefera et al. 2002). After the 1984/85 drought, the government took measures such as enclosure and tree plantations to alter the direction of the LULC change (Tekle 1999; Nyssen et al.

2004; Mekuria et al. 2007). The present study verifies that exclosure coverage has increased considerably while degraded land has decreased. Image analysis also indicated that old forest remnants are intact in only a few areas as thin strips or isolated groves around churches, mosques, and inaccessible areas like very steep mountains and gorges. Isolated forest patches depicted on earlier images indicate severity of forest degradation before the restoration measures. Although population of the area increasing, the current analysis indicated improvement of forest and woody grassland both in cover and density. Conversely, as shown on the 2005 to 2010 satellite data considerable areas have been showing vegetation restoration due to SWC, particularly exclosure interventions. Therefore, as opposed to earlier periods mainly before 1980´s, population growth is unlikely for the current LULC change.

Policy interventions related to deforestation and LULC change in Ethiopia

The way land used and managed is governed by land tenure, ownership right and administrative policies. Elderly people indicated that before the 1975 land tenure reform, land management depended on individual decisions and holdings. Those who had larger holdings kept marginal lands under forest cover, while those with small holdings cultivated these lands and used them for grazing. Moreover, before the land reform, shifting cultivation (*Mofer Zemet Ersha*) was extensively practiced as a strategy to restore soil fertility, thereby maintaining agricultural production. This indicates that the absence of a land use policy and the tenure systems contributed to the conversion of forests and marginal lands to agriculture (Amsalu et al. 2007).

Studies showed extensive deforestation of government-owned forests in the earlier period of the reform (Omiti et al. 1999; Amsalu et al. 2007). Similarly, elderly people indicated that although the 1975 rule urged transfer of land with crops and trees to the new holders, some landlords harvested trees before the transfer. Moreover, following the reform, communal lands were freely accessed by all people. This all resulted in destruction of extensive forest cover immediately after the land reform. The government realized forest degradation and placed the 1980 forest and wildlife development policy. The policy tried to solve the problem through providing forestland ownership right to the public as state, peasant associations and urban dwellers (Anonymous 1980). This shows that great care should be taken with policy reform and structural adjustment in a country like Ethiopia, where larger population depends on subsistent agriculture, otherwise the policy may negatively influence the resources base.

The current government has also implemented policy reforms and carried out structural changes in order to enhance the policies of the previous periods. The transitional government forest conservation, development and utilization as well as rural land administration and use are some among others (EFAP 1994; Anonymous 2005). The rural land administration and use policy attempted to reduce land degradation, facilitate restoration of degraded land and give mandate to regions to develop their own policy taking the federal policy as an umbrella. This shows that managing and utilizing resources are based on local conditions rather than on compliance with general rules, which indicates sustainability concern that considers compatibility of the policy to the local situation. Accordingly, the Amhara region adopted the policy to the actual conditions of the region and declared its own policy, which enforces sustainable use of the land and its resources (Anonymous 2006). The policy demarcates land use based on slope in three categories. It enforces that: i) areas having less than 30% slopes are allowed for cultivation and grazing, ii) areas with 30 to 60% are allowed only for perennial crop cultivation and grass use through cut-and-carry system, and iii) cultivation and free grazing are completely prohibited on over 60% slope (Anonymous 2005). Generally, all laws and regulations by the different governments focus on the importance of natural resources conservation, proper land use and indicate the concern regarding LULC change and the associated impacts.

Thus, it is possible to conclude that the current LULC change and rehabilitation of degraded land in some parts of Wello is largely associated with policy intervention. However, it is important to note that specific policies alone do not lead to improvements unless supported by stakeholder commitment to implement policies and by rising public awareness of the problem.

This study also reflects that rehabilitation rate and intensity was nonlinear regardless of topographic similarity. The spatial variation of rehabilitation could be attributed to the differences in awareness/experience of the problem and/or commitment differences of the local stakeholders to implement a policy. The local-level stakeholders include local authorities (*Kebele* and *Wereda*), community and NGOs working in the area. It was also noticed that involvement of NGOs in resources conservation enhanced community and local authority to implement SWC measures. Moreover, in areas where the successful conservation interventions started earlier, the practices are well replicated. For example, various exclosures in Guba-Lafto, Tehuledere and Dessie-Zuria, Ware-Illu, Ambasel, Jama, Legambo and Tenta, some parts of western Bugna, southeast Gidan, and parts of Mekdla districts particularly along the main highway are well established and in most cases have developed to forest. Therefore, the major driver of the current LULC change in Wello is government policy. However, natural resource conservation policy interventions should be accompanied by intensive awareness rising programs, designing and implementation of alternative livelihood and household energy options.

4.4 Summary and conclusions

SWC interventions such as hillside terracing, exclosure and tree plantations were implemented. Emphasis was put on drought-prone areas, e.g., Wello. Although natural resources restoration has been carried out in the past three decades, the contribution of the interventions to LULC has not been sufficiently studied. Therefore, this study analyzed the spatial and temporal LULC and NDVI change due to the SWC measures, particularly regarding exclosure.

The study was conducted in North and South Wello zones of Amhara National Regional State, and employed a remote sensing approach using MODIS data of 2000 to 2010 to detect LULC and NDVI changes. The MODS data were classified using supervised classification and NDVI spatio-temporal variations analysis. Results of the analysis were compared with a DEM. Both the LULC and inter-annual NDVI change analysis reveal considerable dynamics between 2000 and 2010. The NDVI of the period 2000 to 2010 in selected months (January to April) showed remarkable change. The area covered by a NDVI value of >0.4 increased from 3.6% in 2000 to 16.1% in 2010, whereas NDVI values of 0.3 to 0.4 increased from 27.6% in 2000 to 30% in 2010, which indicate vegetation restoration.

The study area was classified in five LULC types: i) forest, ii) degraded woody vegetation, iii) grassland/woody grassland, iv) cultivated/others land and v) water bodies with 79.2% and 76% classification accuracy level for year 2000 and 2009 images, respectively. The area covered by cultivated/others land, forest and water-bodies showed only very slight change. In contrast, there were considerable differences in the area covered by degraded woody vegetation and grassland/woody grassland. Degraded woody vegetation decreased from 19.7% in 2000 to 6.7% in 2009, while grassland/woody grassland increased by 14.6% in 2009. The DEM indicated that the area of steep and very steep (> 30% slope) landscape accounts for 40%. Larger parts of steep slope landscapes are covered by forest and woody grassland. In the recent years, despite the continued population growth, vegetation cover has shown remarkable improvement, which indicates population growth is no more driving the change. On the other hand, government placed various policy actions to restore degraded lands. Therefore, major driver of the current LULC change is likely attributed to government policy measures concerning SWC. However, differences in policy implementation and rehabilitation showed spatial variation. The variation following government policy implementation could be due to awareness/experience and local stakeholder commitment differences. Local stakeholders include local authorities (*Kebele* and *Wereda*), communities and NGOs. The rehabilitation interventions were found enhanced where people had prior SWC experience and NGOs were involved. The following can be concluded from the analysis:

i. The SWC interventions, particularly exclosure, changed the LULC.
ii. Due to exclosure, vegetation cover of degraded lands had been restored. However, farmers perceived exclosures compete with grazing lands.
iii. The LULC change before 1980´s in Wello was likely attributed to agricultural land expansion due to population growth, while the recent change could be due to government policy interventions in soil and water conservation.

5 PERFORMANCE OF FARMLAND TERRACES IN SOIL FERTILITY MAINTENANCE

5.1 Introduction

The Ethiopian government has realized that drought incidences are largely related to climate change and land degradation. Thus, the government conducted assessments to properly understand the root causes of the problem. The Ethiopian highland reclamation study was one of the first assessments done to understand the root causes and extent of the problem (FAO 1986). The studies indicated that soil erosion is the major causes of the land degradation. As a result, government implemented SWC measures to reduce erosion-induced land degradation (Hurni 1993; Shiferaw and Holden 1999; Tefera et al. 2002). Since then, various mechanical (bunds, terraces, check dams, cutoff drains and waterways) and biological (homestead and communal tree plantations and exclosures) SWC measures have been implemented in drought-prone areas particularly in the eastern and northern highlands (Herweg and Ludi 1999; Badege 2001; Dubale 2001; Amsalu and de Graaff 2007).

Although there have been extensive SWC interventions in recent decades, the practice also exists as indigenous knowledge. The presence of rudimentary and poorly established terraces and lynchets in older aerial photographs of the northern highlands reveals that soil conservation is not a completely new practice (Nyssen et al. 2007). Terracing also has a very long history in few other parts of the country like in the Konso area, which is beloved to be older than 400-years and registered as UNESCO world heritage (Watson and Currey 2009). However, terracing exists in only few areas and in most cases the structures need technical improvement (Nyssen et al., 2007).

There are however, controversies on the advantages and disadvantages of farmland terracing. The performance of farmland terracing, particularly with respect to soil fertility maintenance in the highlands in general and the study area in particular, has not been sufficiently investigated. The few studies show that the performance of farmland terracing to sustain soil fertility varies with topography (El-Swaify 1997) and position within a terrace (Gebremichael et al. 2005; Nyssen et al. 2007). Other studies argue that the impacts of terracing can only be seen over a long period of time (El-Swaify 1997; Sonneveld and Keyzer 2003; Vancampenhout et al. 2006). Generally, there is insufficient empirical evidence related to the impact of farmland terracing on soil fertility over time and space. Therefore, this chapter analyzed impact of farmland terracing with respect to maintaining soil fertility, and evaluated the variability in performance within a terrace, across terrace age and at different terrain positions.

5.2 Material and methods

5.2.1 Study area

The study was conducted in the Maybar Soil Conservation Research Site (MSCRS). This is one of the six sites of the Ethiopian Soil Conservation Research Program (SCRP) established in 1982. The program was conducted by the Ethiopian Ministry of Agriculture (MOA) in cooperation with Berne University, Switzerland (SCRP 2000). The site was selected to represent SWC research in the northeastern highlands of Ethiopia with the aim of testing the suitability and effectiveness of the various SWC measures (Herweg and Ludi 1999; SCRP 2000). It is located in the Lake Maybar watershed in Albiko *Wereda*/district, South Wello zone of Amhara National Regional State about 17 km southeast of the zonal capital, Desse. The watershed is located between 10°58' and 11°02' north latitude and 39°38' and 39°40' east longitude covering nearly 450 ha (Figure 5.1).

The lake drains to the River Borchenna, in the Awash River basin. The watershed is part of the northeastern mountainous area. Geologically, the area is part of the Tarmaber Megezez formation originating from transitional and alkaline basalt (Tefera et al. 1996). According to the FAO classification system (WRB, 2006), the major soils of the watershed are Phaeozems, Regosols, Leptosols, Gleysols and Fluvisols (Weigel 1986). Cambisols, Phaeozems and Leptosols are found on the lower, middle to upper and steeper slopes, respectively. The area receives about 1120 mm mean annual rainfall that on average falls within five months in the two rainy seasons. The mean annual air temperature is 16°C with coolest and hottest temperatures in November (8°C mean daily minimum) and June (26°C mean daily maximum) months, respectively (SCRP 2000). Due to the bimodal rainfall pattern, the area has two cropping seasons. The shorter rainy season is between April and May and the main rainy season is from end of June to end of September (NMSA 1996; SCRP 2000).

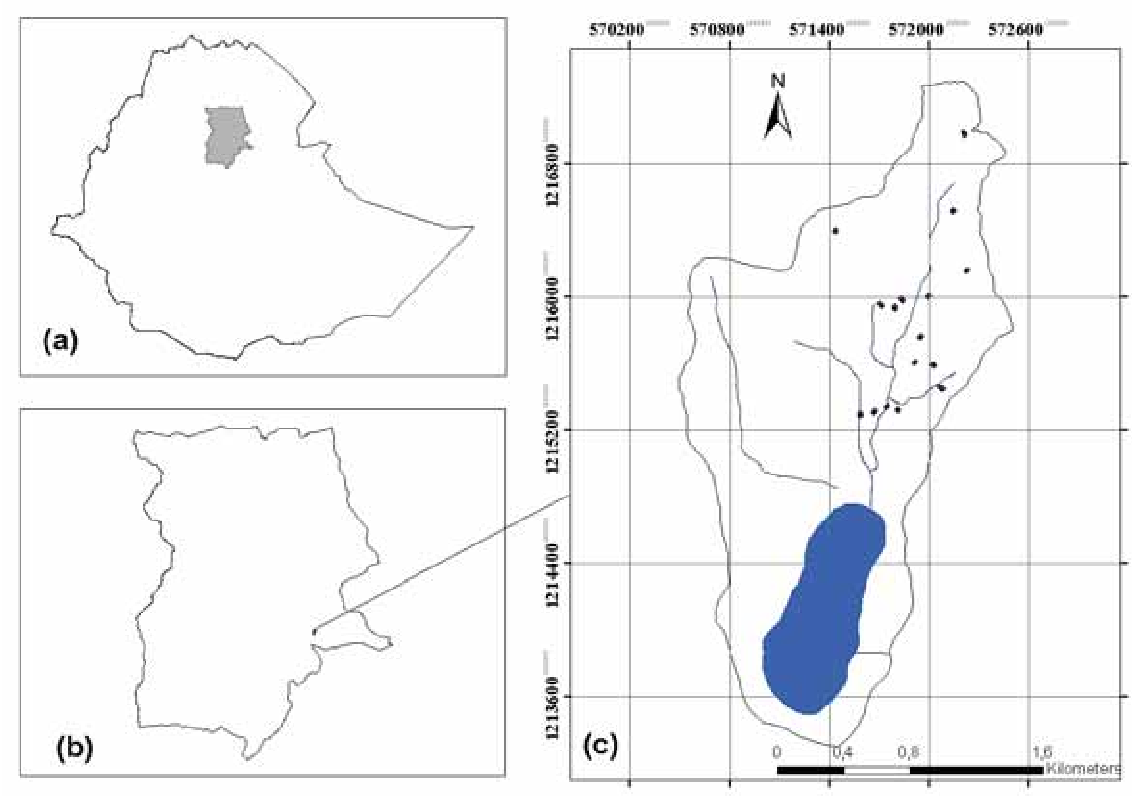


Figure 5.1 Location of study area: (a) Wello in Ethiopia, (b) Maybar watershed in Wello, and (c) Sampling points in Maybar watershed

5.2.2 Sampling site selection and design

A reconnaissance survey was conducted in the north and south Wello zones to identify appropriate sites. The criteria were availability of different-aged farmland terraces in different landscape positions. SWC measures such as terracing have been implemented over large areas at a time through mass community mobilizations. As a result, it was difficult to find terraces of different ages, particularly non-terraced farmland (control) in one or similar watersheds. Moreover, terrace maintenance was based on individual interests, which meant differences on terraces that had however been constructed at the same time in a watershed. Thus, it was decided to conduct the research in the MSCRS, where soil data were available for the time before SWC interventions, and the terraces had been constructed and maintained over a similar period of time. The soil data were used as control to track the changes after the terracing.

The Lake Maybar watershed was classified into different slope categories using a digital elevation model (DEM). The DEM output (Figure 5.2), topographic maps (1:50,000 scale), aerial photograph (1:50,000 scale) and the watershed soil map were used to classify the study area to identify sampling plots. Accordingly, the study site was classified by adopting the FAO system (FAO 2006) of classification into flat to very gently sloping (< 3%), gently sloping (3 - 5%), sloping (5 - 8%), strongly sloping (8 - 15%), moderately steep (15 - 30%) and steep to extremely steep (> 30%). On the MSCRS, experiments are being conducted on 40 fixed plots on slope below 30%. Farmland terraces were constructed, and yields and agronomic practices have been monitored for the last two decades on fixed plots (see Chapter 6). Terracing was deliberately omitted on the land with less than 3% slope because of little erosion on this slope (Hurni 1988). Based on slope, the plots were grouped into four categories, i.e., 3 - 5%, 5 - 8%, 8 - 15% and 15 - 30%. Accordingly, 16 plots representing 4 plots from each slope category were identified. Out of the profile pits of the 1983 soil survey, those on the fixed plot were selected.

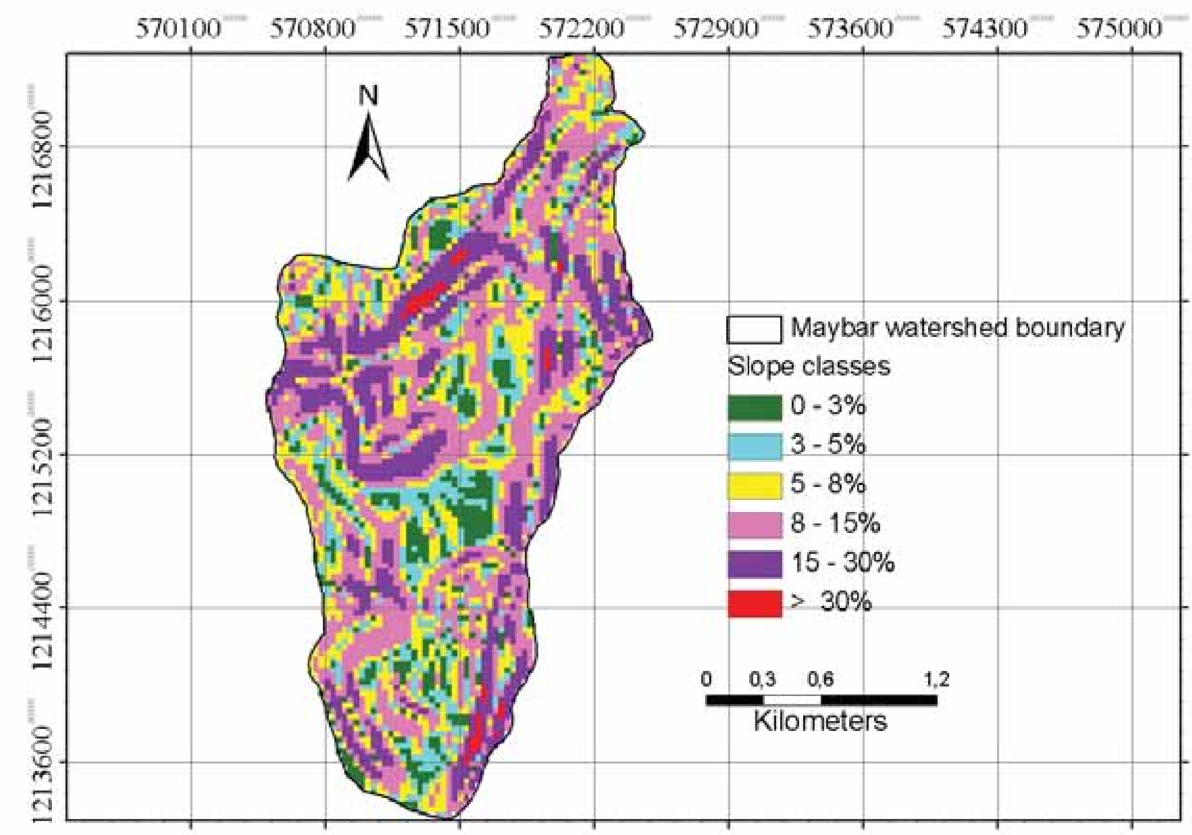


Figure 5.2 Slope map of Lake Maybar watershed

Three sampling positions (Figure 5.3) on the terraces of the fixed plots were selected, i.e., low-terrace (A), mid-terrace (B) and up-terrace (C). The location of the sampling points was as follows: A) low-terrace position refers to the location 50 cm from the lower terrace riser in the upslope direction, B) mid- terrace position is the midpoint between two successive terraces, and C) up-terrace position refers to the location 50 cm from the lower wall of the upper terrace in the down slope direction. The 50 cm distance from both the lower and upper terrace wall was to reduce the effect of water accumulation and splash by the overtopping water, respectively.

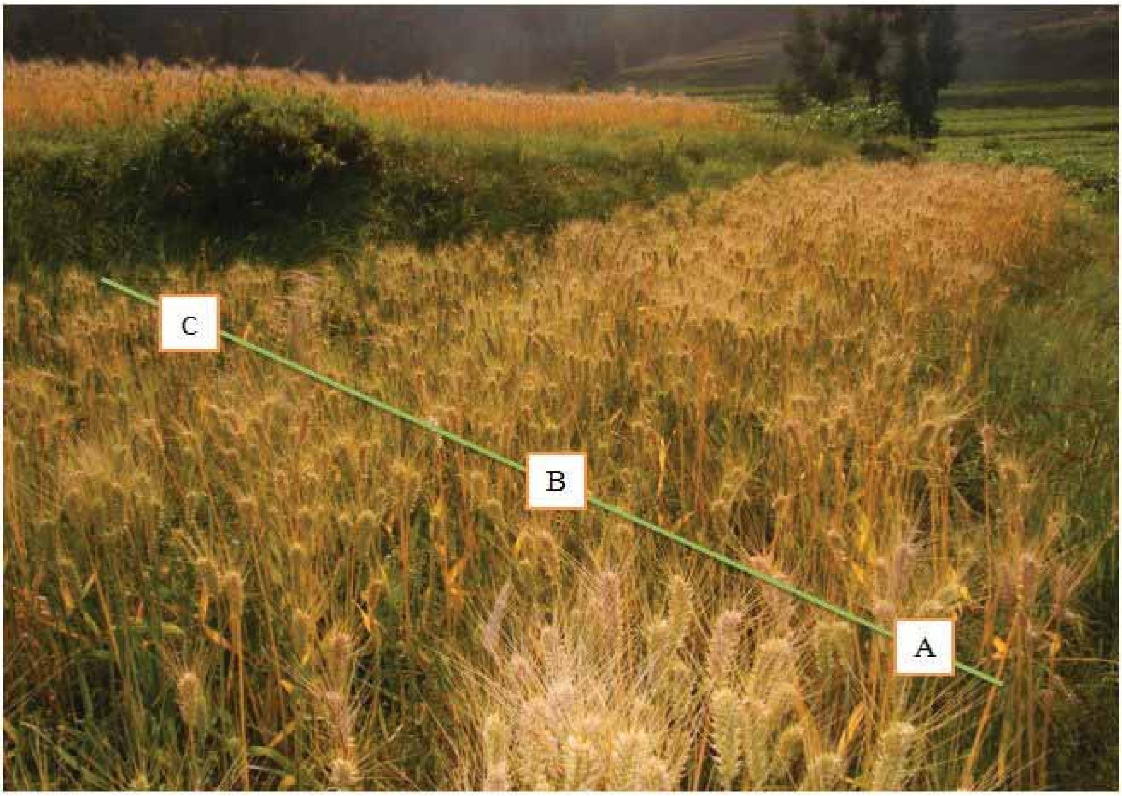


Figure 5.3 Terrace positions: (A) low-terrace, (B) mid-terrace, and (C) up-terrace

5.2.3 Soil sampling, laboratory analysis and reference data

Following identification of sampling plots in the different slope categories and position within the terraces composite soil samples were collected along the terraces at 50 cm distance from the respective auger to 20 cm depth. The samples were thoroughly mixed, composited and bagged (2 kg samples) for laboratory analysis. Undisturbed soil samples were collected using a core ring for bulk density determination. In order to check the soil depth, auguring was continued to 120 cm depth at the center of the sampling plot unless restricted by lithic contact. Characterization and morphological description of properties less affected by the simmering effect of auger such as depth, texture, consistency and color was done as per FAO standards (FAO 2006). Sampling was done from four slope categories, in four replicates (plots) and in three terrace positions (Table 5.1). Thus, a total of 48 samples were collected for laboratory analysis. Regarding bulk density sampling, three core ring samples could not be taken from one plot on the 15-30% slope due to the gravely soil there. Hence, the bulk density test was done only for 45 samples. Other management practices such as use of fertilizer, manure and compost and crop residue management was obtained from the seasonal monitoring records of the research station.

Table 5.1 Farmland terrace soil sampling design

Slope	Replicates												Total
(%)	Replicate 1			Replicate 2			Replicate 3			Replicate 4			samples
3-5	A	B	C	A	B	C	A	B	C	A	B	C	12
5-8	A	B	C	A	B	C	A	B	C	A	B	C	12
8-15	A	B	C	A	B	C	A	B	C	A	B	C	12
15-30	A	B	C	A	B	C	A	B	C	A	B	C	12*
Grand total													48

Note: *A = low-terrace, B = mid-terrace and C = up-terrace positions*

** Only 9 core ring samples were collected from plots in 15 – 30% slope range*

The composite soil samples were air dried, crushed and sieved through a 2 mm mesh. The main soil physical and chemical properties such as texture, pH, electrical conductivity (EC), organic carbon (OC), available phosphorus (av. P), total nitrogen (TN), exchangeable bases such as exchangeable calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}) and sodium (Na^{+}) and cation exchange capacity (CEC) were determined from the composite samples while bulk density was determined from the core ring samples. Soil bulk density was determined by the Black (1965) method. Soil reaction (pH and EC) and soil particle-size distributions were determined using glass electrode and hydrometer, respectively by Van Reeuwijk (2002) method. OC was determined by the Walkley and Black (1934) method, TN by the Kjeldahl method as described in Black (1965) and available P by Olsen et al. (1954) methods. Exchangeable bases (Na^{+}, K^{+} Ca^{2+}, and Mg^{2+}) and CEC were determined by the ammonium acetate method at pH 7 as described by Rowell (1994). The analysis was done at the National Soils Testing Laboratory in Addis Ababa, Ethiopia.

Data from the MSCRS soil survey conducted before terracing in 1983 were used as a baseline (Weigel 1986). The profiles were grouped and selected according to the study plan. Accordingly, the topsoil analysis results reported by Weigel (1986) were averaged and used for the comparison. Since the baseline data did not fully match with the current sampling design, the terrace-age effect on soil fertility was not statistically analyzed.

5.2.4 Statistical data analysis

The soil laboratory data were statistically tested by analysis of variance (ANOVA) in SPSS version 17. A general linear model (univariate) was used taking soil analysis data as dependent variables and the slope of the land and positions within the terrace as fixed factors. The model is given as:

$$y_{ij} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ij} \tag{5.1}$$

Where y_{ij} = dependent variable (soil physico-chemical properties), μ = sample mean, α_i = effect of slope, β_j = effect of terrace position, $(\alpha\beta)_{ij}$ = effect of slope and terrace position interaction, and ε_{ij} = random error

The model was evaluated by the likelihood-ratio test to decide whether to retain or reject interaction of fixed factors in the model. The test revealed that the full model, which considers interaction of factors, had higher values. This indicates that the observed outcome was more likely to occur under the full than under the reduced model, thus the full model was retained. In order to test the correlation of the different soil properties, a bivariate correlation analysis was done in SPSS version 17.

5.3 Results and discussion

5.3.1 Biophysical changes after farmland terracing

The field observations revealed that SWC measures have been widely implemented in Wello and most of the structures are stabilized. Stability of SWC structures depend on various factors such as slope of the land, construction quality, construction material, support of physical structures by biological measures, and appropriateness of structure to the site conditions (El-Swaify 1997; Zhang et al. 2004; Olarieta et al. 2008). For example, appropriateness of SWC structures with increasing slope comes in the order of soil bund, stone-faced bund, stone terrace, bench terrace and hillside terrace, respectively (Cao et al. 2007; Nyssen et al. 2007). Most of the terraces in the study site have become bench terraces, and grasses growing on the terraces also stabilized the structures. Measurements to estimate the slope gradient between the edges of terraces (low- and up-terraces walls) indicated nearly level conditions, mostly <2%. Regular sedimentation and maintenance resulted in the development of higher terraces on steeper slopes due to great relief differences within shorter distances.

Distinct terraces height differences were observed across the landscape. Terraces over 180 cm and as short as 40 cm were observed on the upslope and lower slope positions, respectively (Figure 5.4). As reported by other authors, the terrace height differences resulted in soil depth gradients across the slope of the land (Gebremichael et al. 2005; Nyssen et al. 2007). Terraces on steep slopes are not only higher but are also made up of large boulders and stones, that form thick stone walls (Figure 5.4a) as opposed to those on the lower slopes, where they mostly consist of short and narrow strips of soil bunds or stone-faced soil bunds (Figure 5.4 b). Similarly, other authors reported that closely spaced and taller structures are constructed on the steep slopes however, such structures are limited as the slope becomes very steep (Zhang et al. 2004; Olarieta et al. 2008; Nyssen et al. 2007). Soil depth gradients were also observed within a terrace, where a deeper soil profile was measured at the down-slope positions.

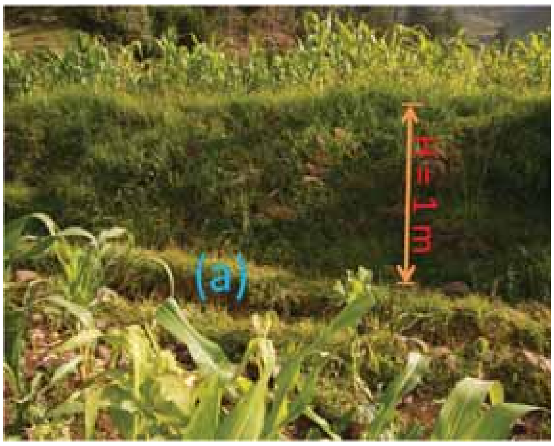


Figure 5.4 Partial view of farmland terraces: (a) Well developed terrace wall and (b) Terraces across the landscape

Terracing resulted in soil depth improvement as compared to the depths reported in the 1983 survey. More than 80% of the auger drillings of this study revealed over 120 cm soil depth at low-terrace positions and the remaining 20% a minimum of 80 cm depth, while in the 1983 survey soil depths of less than 120 cm were found in less than 50% of the profiles. Active gullies and stream banks (Figure 5.5a and c) existing at the start of the MSCRS project were well stabilized and covered by vegetation at the time of the study (Figure 5.5 b and d). There have also been marked terrain modifications and biophysical changes (Figure 5.4 and Figure 5.5). The presence of non-angular and different-size (very fine to medium) gravels in the soil profile indicates erosion and deposition processes within the watershed. The gravel volume and diameter change with the general slope of the land reveal the deposition patterns across the landscape. Coarser material was found in terraces adjacent to river courses and on upslope positions, while fine-textured soils were found in the down-slope positions.

(a) Active gully (source MSCRS, 1983)

(b) Stabilized gully (June 2010)

(c) Stream bank (source MSCRS, 1983)

(d) Stablized stream bank (June 2010)

Figure 5.5 Gully and stream bank before (1983) and after (2010) SWC interventions in Lake Maybar watershed

5.3.2 Soil fertility variation on farmland terraces across the terrain

Terracing modifies terrain conditions by changing slope angle and length. Consequently, terracing influences soil properties by changing soil erosion and deposition processes. Accordingly, soil properties were significantly different across the slope of the terrain. Soil pH is the first parameter to be considered in soil fertility evaluation, while EC is important to determine the salinity level. Generally, the pH values were nearly neutral with a mean pH [H_2O] of 6.7. Values on the farmland terraces significantly ($P < 0.001$) decreased with increase in slope of the terrain. Multiple comparisons (Tukey HSD test) showed that the terraces in the lower slope positions had statistically significantly higher soil pH than those in the upper slope positions. For example, the terraces on gently sloping and moderately steep terrain had soil pH [H_2O] of 7.0 and 6.5, respectively. However, the pH differences between terraces on moderately steep and gentle sloping terrain were small (ΔpH [H_2O] ≈ 0.6). The change in soil pH in both solutions (pH [H_2O] and pH [KCl]) showed a similar trend across the landscape and between terraces of successive slope categories (Table 5.2). Soils showed higher acidity on the 8-30% slope than on the 3-8% slopes. But the pH differences between different slopes were too small to cause differences in plant nutrition status and heavy metals toxicity (Dong et al. 1995; Xu et al. 2006).

Similarly, soils of the terraces located on different slopes showed statistically significant EC differences. Soils of the terraces on gently sloping (3-5%) land had statistically significantly higher ($P = 0.008$) EC than those on the terraces on moderately steep slope (15-30%). However, the differences were very small, and values were too low (mean EC of 0.08 ds/m) for adverse effects on the plants (Barbiéro et al. 2001). Due to topographic influences, exchangeable bases could be leached down the soil profile or washed out through runoff; as a result soil pH decreased toward the upslope terrain positions.

Table 5.2 Average (n = 12) soil properties in 0-20 cm depth on terraces across slope of the terrain

Slope (%)	pH (H_2O)	pH (KCl)	EC (ds/m)	TN (%)	OC (%)	av. P (ppm)	CEC (cmol(+)/kg)
3-5	7.0^{daa}	5.3^{baa}	0.10^{bdb}	0.18	1.45^{ddb}	15.2	42.5^{dbd}
5-8	6.9^{aa}	5.1^{ad}	0.07^{dd}	0.18	1.42^{db}	10.4	43.3^{bd}
8-15	6.4^{d}	4.8^{b}	0.08^{d}	0.18	1.47^{b}	6.8	46.8^{b}
15-30	6.5	5.0	0.07	0.21	1.97	16.1	42.3
F^{-value}	22.50^{***}	22.57^{***}	4.62^{**}	1.30^{ns}	4.56^{**}	2.04^{ns}	5.81^{**}

Slope	Exchangeable bases (cmol(+)/kg)				Db	Particles size distribution (%)		
(%)	Na^+	K^+	Ca^{2+}	Mg^{2+}	(g/cm^3)	Sand	Silt	Clay
3-5	0.40^{dcb}	0.54^{ddd}	24.2	5.12	1.35	19^{dbb}	36^{bdd}	45^{dbb}
5-8	0.36^{dd}	0.69^{bb}	23.7	5.53	1.33	18^{bb}	40^{cb}	42^{dd}
8-15	0.24^{d}	0.36^{d}	24.7	5.50	1.32	28^{d}	36^{d}	36^{d}
15-30	0.22	0.38	22.8	4.90	1.41	27	36	37
F^{-value}	3.43^{**}	6.52^{***}	1.66^{ns}	1.04^{ns}	0.39^{ns}	6.94^{***}	4.53^{**}	5.18^{**}

Note: *The superscripted letters (a, b, c, d) indicate that soil properties of a given slope range are different (a) at P = 0.01, (b) at P = 0.05, (c) at P = 0.1 and (d) non-significantly different from the subsequent slope ranges (Tukey HSD).*

For example, in the 1st column and 1st row pH (H2O) = 7.0^{daa} *indicates that soil pH* (H_2O) *differences on terraces located at 3-5% slope terrain is non-significantly different than that of the 5-8% slope (d). But the soil pH* (H_2O) *on terraces located at 3-5% slope terrain was statistically significantly higher than that of the 8-15% slope (a) at P = 0.01 level and also significantly higher than that of the 15-30% slope terrain (a) at P = 0.01 level.*

*F-value is *** significant at P = 0.01, ** significant at P = 0.05 level, * significant at P = 0.1 level, and ns non-significant*

EC = electrical conductivity, TN = total nitrogen, OC = organic carbon, av. P = phosphorus (available), CEC = cation exchange capacity, Db = bulk density

The statistical analysis revealed that the soils of the farmland terraces had statistically significantly different CEC (P = 0.002), exchangeable Na^+ (P = 0.027) and K^+ (P = 0.001) content across the terrain (Table 5.2). On the other hand, exchangeable Ca^{2+} and Mg^{2+} did not show statistically significant differences with slope change. Generally, contents of soil exchangeable bases were low and showed a decreasing trend with slope increase (Figure 5.6). For example, exchangeable K^+ ranged from 0.1 cmol (+)/kg to 1.27 cmol (+)/kg with an average of 0.49 cmol (+)/kg. The highest exchangeable K^+ level measured in the topsoil of the study area was 1.27 cmol (+)/kg, which is equivalent to 0.45 kg K^+ t^{-1} soil. This indicates that the soils have a low exchangeable K^+ level (Alexander 1991; Bergmann 1992; Sys et al. 1993). Soils on the 5-8% slopes had statistically significantly higher ($P \leq 0.005$) exchangeable K^+ than on the 8-30% slope. However, differences in exchangeable K^+ ($\Delta K^+ \approx 0.12$ kg K^+ t^{-1} soil) between terraces on gentle and steep slopes were too low to cause relevant fertility differences. In contrast, CEC showed an irregular trend across the slope of the land. In-depth comparison indicated that soils of the terraces on 8-15% slopes had statistically significantly higher CEC ($P < 0.05$) than those on the other slope. Soil CEC of the terraces across slope of the terrain ranged from 42.3 cmol (+)/kg to 46.8 cmol (+)/kg.

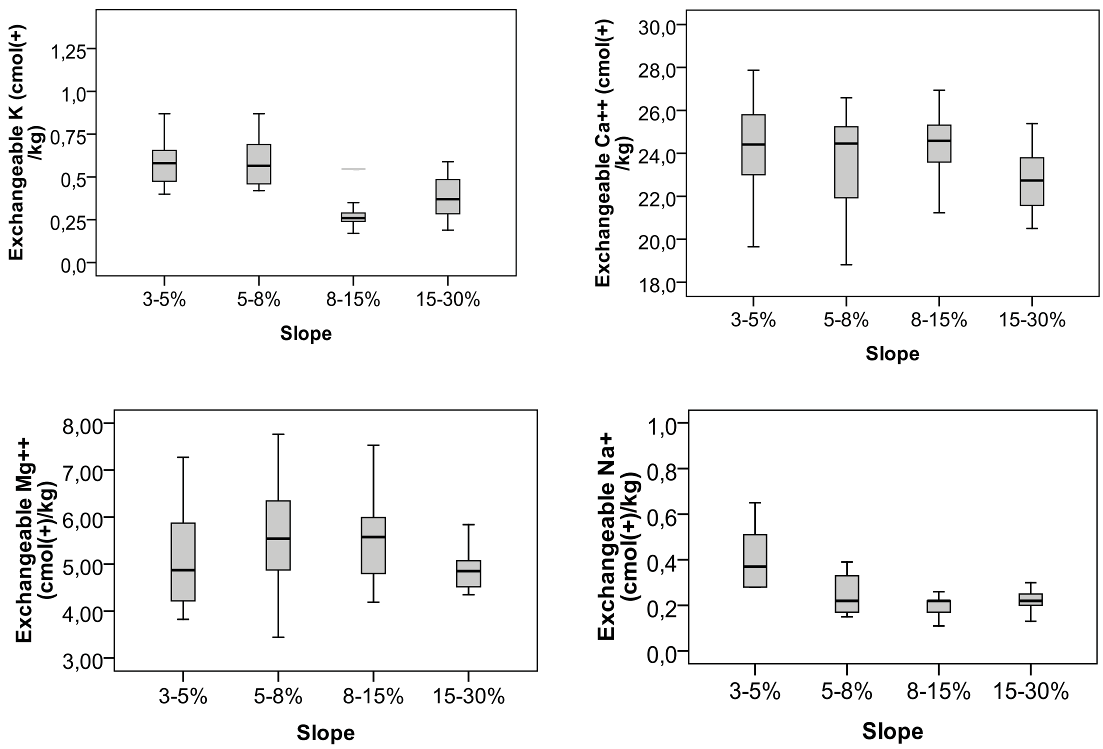


Figure 5.6 Soil exchangeable bases on terraces across the terrain

The differences in contents of exchangeable bases within a given watershed could depend on variation in parent material or micro-climate and/or erosion (Chen et al. 1997; Olarieta et al. 2008). Since Lake Maybar watershed has a uniform geology (basalt) and micro-climate; neither geology nor micro-climate contributed to the exchangeable bases (K^+ and Na^+) differences across the slope of the terrain. Statistically significant differences in the values between terraces of different terrain position could be attributed to erosion, deposition and leaching processes. Erosion and leaching remove soluble salts from upper-slope and accumulate these at the down-slope positions (Pimentel et al. 1995). Pimentel et al. (1995) reported that soil transported through erosion could contain a threefold higher nutrient amount than soils remaining behind.

Even if runoff is slow at the down-slope positions, the solutes need adequate time to precipitate. Thus, exchangeable base suspensions may not have time to precipitate into the soils of terraces located at the upper-slope positions, and the exchangeable bases could therefore be washed down the slope.

Erosion, leaching and accumulation of soluble salts are determined by topographic conditions and surface-water and groundwater flow directions (Chen et al. 1997; Olarieta et al. 2008). At the lower slope positions, water has a relatively longer residence time and as a result, soluble materials precipitate down (Olarieta et al. 2008). Consequently, relatively higher contents of soil exchangeable bases were observed in terraces located on 3-8% slope (Chen et al. 1997). It can thus be deduced that terracing could be unlikely to enhance *in-situ* conservation of soil exchangeable bases. Rather, terracing may play an important role in enhanced deposition of eroded or leached bases within a watershed, particularly in the soils of terraces located on flat land or gentle slopes. Exchangeable bases lost via erosion and leaching from upper slope terraces may partly be deposited in the watershed at down slope.

Terraces in the lower slope areas have gentler slopes and wider spacing, and as a result the incoming runoff could remain for longer period and partly deposit suspended and dissolved materials. If the terraces were not there, sediment-loaded runoff would continue to flow down the slope until it encountered low-lying land or a stream course. Generally, statistically significant differences in soil pH and exchangeable bases on the terraces across the terrain could be largely attributed to erosion and/or leaching of basic cations from the steep slope to flat and/or gentle slope positions. However, the small differences between terraces located on upper and lower slope positions could be due to the inherent soluble salt level of the soils. The CEC of soil is the result of the interactive effect of different soil attributes such as exchangeable bases, clay and organic colloids. Thus, it was not clear which property influenced the CEC differences across the terrain.

Soil organic matter (OM) determines soil quality, physical properties, crop nutrition and the link between these (Bergmann 1992; Loveland and Webb 2003). The soil physical properties affected by soil OM include aggregate stability, infiltration, water-holding capacity, soil workability, bulk density, aeration and water movement (Bergmann 1992; Loveland and Webb 2003). The analysis revealed a low OC (mean

OC = 1.58 %) content and slight increase with slope of the terrain. Loveland and Webb (2003) reported that a 2% soil OC is a critical level for crop production and soil aggregate stability. The OC content increased significantly ($P = 0.008$) with increase in slope. However, TN and plant-available P did not show significant changes with slope. Although soil OC content increased with slope, the increase was not uniform but skewed (Table 5.2). A comparison between terraces for different slope categories revealed statistically significant OC differences between terraces on moderately steep slopes (15-30%) and terraces in the other slope categories ($0.016 \leq P \leq 0.034$) with mean differences of 0.50% to 0.56%. Nevertheless, soil OC content differences (0.50% ≤ mean ΔOC ≤ 0.56%) between terraces were too small to cause fertility gradients. The differences could be related to input differences.

The farmlands on the moderately steep slopes are near to exclosures and/or grasslands. These terraces could gain additional OM due to natural erosion. Terraces could significantly reduce further transportation of the added litter from non-arable land situated above. The difference in OC content could possibly be related to input differences and effect of terracing. Terracing reduced soil erosion and improved deposition and trapped material such as plant litter. Hence, the plant litter transported from non-arable land covered by trees or grasses could be stopped by the terraces at the upper slope from further translocation. The overall low OC level could be due to oxidation as a consequence of continued tillage and residue removal (Bergmann 1992; Loveland and Webb 2003). Unless soil nutrient export is compensated for through use of fertilizer, residues and manure, OC degradation will continue (Gabrielle et al. 2005).

The statistical analysis also revealed that TN and available P showed non-significant differences across slope. Nevertheless, values followed the same trend as OC across slope of the terrain (Table 5.2). The Pearson correlation revealed positive, significant ($P = 0.01$) and strong ($r2 = 0.9$) correlation of OC and TN (Table 5.3). The correlation between OC and TN indicate their interdependency. The topsoil on average had 1.9 kg t^{-1} (0.19%) TN, a little higher than the absolute minimum (Alexander 1991; Bergmann 1992; Sys et al. 1993). Like OC, higher TN (mean 0.21%) contents were measured in the soils of the moderately steep slopes (15-30%) than those on less than 15% slopes (mean TN of 0.18%). The difference in soil TN between terraces of moderately steep slopes and the other two middle slope categories was too small

(0.03%) for tangible differences in plant nutrition. Furthermore, nearly all terraces of all slope categories had the same TN mean difference ($0.03 \leq$ mean $\Delta TN \leq 0.035$). The explanation given above for OC differences across the terrain also holds true for TN.

Table 5.3 Correlation between soil physico-chemical properties of farmland terraces

	pH	Db	Clay	Na	K	Ca	Mg	CEC	T.N.	O.C
Db	0.054									
Clay	0.175	0.043								
Na	0.376**	0.232	0.309*							
K	0.327*	0.005	0.147	0.562**						
Ca	0.121	-0.209	-0.076	0.087	-0.096					
Mg	0.116	-0.219	0.232	-0.013	-0.144	0.307*				
CEC	-0.270	-0.305	0.030	-0.078	-0.267	0.339*	0.502**			
T.N	-0.410**	0.010	0.424**	0.043	-0.027	-0.314*	-0.026	0.188		
O.C	-0.404**	-0.064	0.268	-0.018	-0.132	-0.352	-0.047	0.185	0.898**	
av P	0.132	-0.196	0.039	0.005	0.195	0.004	-0.092	-0.126	0.036	0.212

** *Correlation was significant at the 0.01 level (2-tailed).*
*. *Correlation was significant at the 0.05 level (2-tailed).*
Values are Pearson correlation coefficient (r) n= 48

Soil available P contents (av. P = 12.1 ± 3.1 ppm, i.e., av. P = 12.1± 3.1g/ton) of the terraces was smaller than the absolute minimum. Watson and Mullen (2007) suggested that 15 ppm (15 g/ton) is a critical soil P concentration for categorizing the soil as P sufficient or deficient. But this does not mean same critical P value for all crops in all soil types where the levels vary with crop and soil types (Bergmann 1992; Sys et al. 1993). The lower plant available P could be attributed to inherent soil properties such as P fixation by iron and aluminum, while the differences between the terraces across slope of the terrain could be related to organic matter (OM) input differences. Higher OC, TN and available P contents were observed on terraces located at moderately steep slope positions.

Texture and bulk density contribute to crop productivity as they affect soil physical fertility (Hamza and Anderson 2002; Rasool et al. 2007). The soil physical properties influence soil water movement, root penetration and nutrient uptake (Hamza and Anderson 2002; Rasool et al. 2007). Erosion and deposition processes also modify soil physical characteristics (Chen et al. 1997; Vancampenhout et al. 2006). The analyses in the present study revealed statistically significant ($P < 0.01$) soil texture differences between terraces located on different slopes. However, soils did not show significant bulk density differences with slope change. The content of sand particles in the soils statistically significantly increased with increase in slope of the terrain (Figure 5.7). Terraces on 8-30% had statistically significantly higher ($P \leq 0.01$) sand content than on the 3-8% slopes. However, terraces in successive slope categories both on 3-8% and 8-30% slopes showed non-significant differences (Table 5.2). Terraces on the 5-8% slopes had statistically significantly higher ($P < 0.07$) silt contents than terraces on the 3-5% and 8-30% slopes. In contrast, clay content decreased with slope increase. Terraces on the 3-8% slope had significantly higher ($P \leq 0.023$) clay contents than terraces on the 8-30% slope. The mean clay content differences varied from 5% to 6%. Terraces on the sloping (5 - 8%) terrain had statistically significantly higher clay contents than terraces on 8-15% slope, with 6% mean difference.

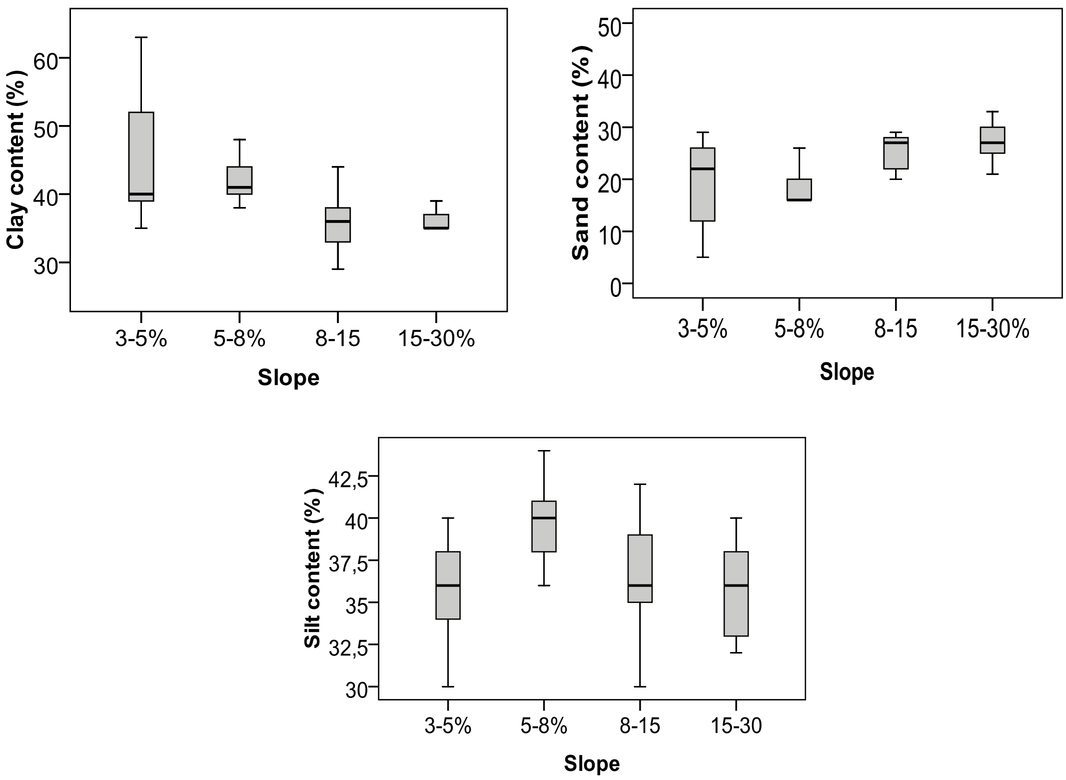


Figure 5.7 Soil textures of terraces across slope of the terrain

Soil texture differences between terraces at different slope could be related to erosion and deposition processes. The highest silt content was measured in soils on sloping terrain may be resulted to erosion and sedimentation processes, as there could be a balance between soil particle detachment, runoff velocity and deposition. Sheet erosion induces selective removal of soil particles on steeper slopes living behind coarser materials (sand, gravel, stones), while the transported material is deposited as the slope steepness decreases. Medium-sized soil particles (very fine sand and silt) settled ahead, while finer particles (mainly clay) and solutes (soluble salts) settled on the flatter slope, as the runoff water stayed for a relatively longer period or flowed at a considerably slower speed or the accumulated water infiltrated down (Gebremichael et al. 2005). The soil texture pattern across the slope of the terrain indicates that terracing did not prevent an accumulation gradient; nevertheless it considerably reduced water-erosion-induced texture gradients.

5.3.3 Soil fertility variation at different positions within a terrace

Among physico-chemical properties analyzed, only bulk density and pH [KCl] showed statistically significant differences between the three terrace positions. The soil properties that showed non-significant differences include OC, TN, exchangeable bases, CEC, pH [H_2O] and texture (Table 5.4). This trend is different from reported by other studies, where the studies reported statistically significant nutrient gradient across a terrace (Gebermichael et al. 2005; Vancampenhout et al. 2006; Nyssen et al. 2007). At the beginning of terrace construction the basins excavated in front of the terrace risers (in the upslope direction) not only reduce the energy of incoming runoff but also serve as a storage tank for sediment-loaded runoff. Consequently, the water detained in the basin and at the low-terrace position would have adequate time to unload the sediments and infiltrate into the soil (Gebermichael et al. 2005; Vancampenhout et al. 2006; Nyssen et al. 2007). Thus, a soil accumulation gradient develops until the slope differences between the two edges of the terrace are minimized (Gebermichael et al. 2005). These processes cause higher sediment accumulation in front of terraces at the beginning of terrace construction, which results in nutrient gradient within a terrace. However, the accumulation decreased with terrace development. In the study site, it was observed that farmers keep increasing terrace heights until formation of bench terraces. This leads to a considerable slope difference reduction across a terrace. The slope gradients measured across the terraces in the study site were mostly less than 2%. With the slope gradient reduction, the incoming runoff has been distributed uniformly, thus the runoff have adequate time to deposit the sediments uniformly throughout the terrace (Herweg and Ludi 1999; Gebermichael et al. 2005; Cao et al. 2007).

Table 5.4 Average (n = 16) topsoil (20 cm depth) properties across terraces

Position	pH (H_2O)	pH (KCl)	EC (ds/m)	TN (%)	OC (%)	av. P (ppm)	CEC (cmol(+)/kg)
A	6.6	4.96^{dc}	0.09	0.18	1.56	13.5	43.7
B	6.7	5.02^{d}	0.07	0.18	1.48	11.1	43.0
C	6.8	5.09	0.07	0.19	1.69	11.8	44.4
F^{-value}	2.267^{ns}	2.90^{*}	2.15^{ns}	0.221^{ns}	0.974^{ns}	0.214^{ns}	0.899^{ns}

Position	Exchangeable bases (cmol(+)/kg)				D_b	Particles size distribution (%)		
	Na^+	K^+	Ca^{2+}	Mg^{2+}	(g/cm^3)	Sand	Silt	Clay
A	0.24	0.49	23.9	5.15	1.2^{ad}	21	38	41
B	0.35	0.51	23.8	5.07	1.6^{a}	24	37	39
C	0.32	0.48	23.8	5.56	1.2	24	36	40
F^{-value}	1.71^{ns}	0.09^{ns}	0.014^{ns}	1.04^{ns}	14.78^{***}	0.703^{ns}	0.926^{ns}	0.313^{ns}

Note: *A = low-terrace, B = mid-terrace, C = up-terrace positions; for other abbreviations and significance levels see Table 5.2*

But this does not mean that soil depths in terraces are the same. In fact, they decrease in upslope direction. A soil depth gradient develops during the early stage of sediment accumulation. As the terraces develop to bench terraces, the topsoil receives a proportionally similar sediment load and has a uniform topsoil nutrient status. As a result, non-significant topsoil fertility differences between the three positions of the terraces were observed. Thus, it could be concluded that the topsoil fertility gradient within a terrace decreases during this process. However, it also important to note that bench terrace formation does not prevent volumetric soil and nutrient differences within a terrace. The topsoil fertility uniformity occurs as elevation differences within a terrace reduce to a minimum level. Soil profile depth variations definitely result in overall soil nutrient and moisture reserve gradients.

In contrast, bulk density (D_b) significantly differed ($P < 0.001$) at the three terrace positions. The average soil D_b of the farmland terraces was 1.35±SD gm/cm^3. The highest value (1.6 gm/cm^3) was measured at the mid-terrace position while the two edges of the terrace had nearly equal D_b. The average D_b measured at the low- and up-terrace positions were 1.21 gm/cm^3 and 1.24 gm/cm^3, respectively. The ΔD_b between the mid- and the two edges of the terraces was nearly 0.4 gm/cm^3. The mid-terrace positions had not only higher D_b but smaller standard deviation. This indicates that most terraces had higher D_b at the mid-terrace positions (Figure 5.8).

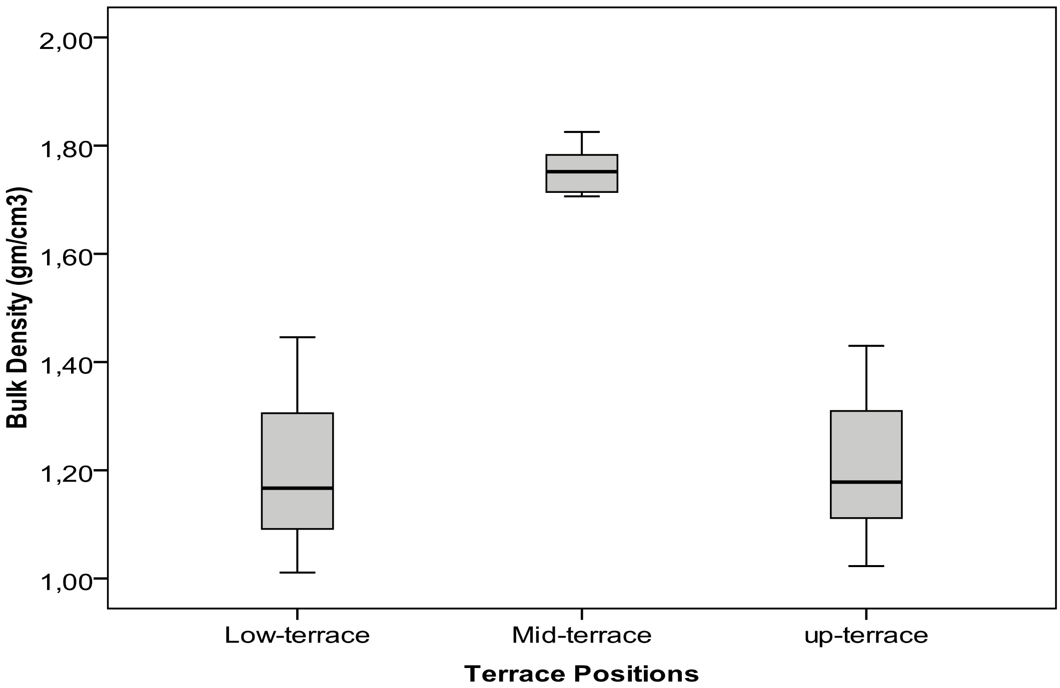


Figure 5.8 Soil bulk density variability across terraces

The higher standard deviation between soil bulk densities of the two edges of the terraces indicates existence of wide variation among terraces. On the other hand, D_b at the mid-terrace position had a smaller standard deviation as compared to the D_b at the two edges of the terraces, which indicates that terracing had a similar compaction effect at the mid-terrace position (Figure 5.8). Bulk density differences ($\Delta D_b \approx 0.4$ gm/cm^3) between the midpoint and the two edges of the terraces likely to influence soil physical properties, particularly soil-water movement, aeration and root proliferation (Kaufmann et al. 2010). According to Kaufmann et al. (2010), critical D_b above which plant root development is affected range from 1.4 gm/cm^3 in clay soils to 1.8 gm/cm^3 in soils coarser than loamy sand. Clay and OC content differences (Δclay ≈ 2% and ΔOC ≈ 0.21%) between mid-terrace positions and the two edges of the terraces were very small. Moreover, the D_b also correlated insignificantly with both clay and OC. Very low content and the non-significant correlation of soil OC with D_b within a terrace could indicate that it is unlikely to has a relevant influence on D_b (Catherine and Ouimet 2007; Keller and Håkansson 2010). Statistically significantly higher D_b at the mid-terrace position could be due to differences in soil aggregate packing. On average sand, silt and clay contents at the mid-terrace positions were 24%, 37% and 39%, respectively. Keller and Håkansson (2010) reported that the mechanical behavior of soil changes at about 29.3% clay content. A nearly proportional soil particle distribution could enhance soil packing and thereby result in a higher D_b. With the development of bench terraces, sediments are deposited uniformly across the terrace, thus the mid-terrace receives average sized-particles. The proportional soil aggregates received at the mid-terrace positions could enhance packing of soil voids and thereby increase D_b. Hence, higher soil D_b at the mid-terrace positions could be attributed to the soil aggregates received. On the other hand, the proportional sediment deposition at the mid-terrace positions indicates the balance between erosion and deposition within a terrace.

Soil pH [KCl] also showed statistically significant differences (P = 0.07) between the three terrace positions. Values tended to increase in the upslope direction where the lowest pH was measured just at the low-terrace positions and the highest at up-terrace positions. The mean soil pH [H_2O] ranged from 6.6 low-terrace to 6.8 at the up-terrace positions. However, the pH differences (ΔpH [KCl] $\approx$ 0.13 and ΔpH [H_2O] $\approx$ 0.2) low-terrace and up-terrace positions were too small to cause differences in soil nutrition status and heavy metals toxicity (Dong et al. 1995; Xu et al. 2006).

5.3.4 Soil fertility variation with age of farmland terraces

The results of the present study reveal nearly stable soil nutrient levels over two decades of farmland terracing at the MSCRS. There was a slight decline in some nutrients while others showed an increasing trend. Soil properties showed a decreasing trend were OC, exchangeable bases and bulk density. On the other hand, an improvement was observed in soil pH and TN. Accordingly, on average, soil acidity decreased (pH increased 6.4 to 6.7) and TN increased 0.16 to 0.19%. However, other soil properties such as OC, exchangeable bases and av. P showed a decreasing trend: OC declined from 1.98% to 1.58% while av. P dropped by 5.16 ppm (5.1 g/ton). Likewise, exchangeable K^+, Ca^{2+} and Mg^{2+} decreased by 0.15 cmol (+)/kg, 10.35 cmol (+)/kg and 6.01 cmol (+)/kg, respectively. Average bulk density increased from 1.02 g/cm^3 to 1.35 g/cm^3. Generally, the soil nutrient status showed a slightly declining trend with time (Table 5.5). The soil bulk density differences with age of terraces and within a terrace showed clear differences. This analysis clearly demonstrates that terracing reduced soil loss through water erosion, and consequently erosion and deposition processes led to changes in soil bulk density, i.e., caused compaction particularly at the mid-terrace position.

Table 5.5 Soil properties in 1983 and 2010 at the study site

Soil property	Mean value (1983)	Mean value (2010)	Difference (2010 – 1983)
pH [H2O]	6.44	6.71	0.27
DB (gm/cm3)	1.02	1.35	0.33
OC (%)	1.98	1.58	-0.4
TN (%)	0.16	0.19	0.03
Na+ (cmol (+)/kg)	0.18	0.31	0.13
K+ (cmol (+)/kg)	0.64	0.49	-0.15
Ca2+ (cmol (+)/kg)	34.19	23.84	-10.35
Mg2+ (cmol (+)/kg)	11.58	5.26	-6.01
av. P (ppm)	17.27	12.11	-5.16

Source: *Soil survey report of MSCRS (Weigel, 1986)*

The SWC interventions lead to reduced soil and nutrient loss through erosion (Hurni 1993; Haileslassie et al. 2005; Vancampenhout et al. 2006). In the study area, interventions for maintaining soil fertility such as use of organic and inorganic fertilizer and practices that enhance nutrient recycling are still much below the existing nutrient depletion rate. In the MSCRS and most parts of the Ethiopian highlands both grain and residue are harvested. The crop residue is used as livestock feed, and animal dung is used for household energy and not returned to the farmlands. Moreover, traditional fallowing is currently hardly practiced, and farmlands are cultivated two times a year with very low or no fertilizer use. The SWC structures are also not completely sediment proof, and the effectiveness of the structures varies with slope and structure type. For example, Herweg and Ludi (1999) reported 0.5 t ha^{-1} to 3.3 t ha^{-1} annual soil loss under different SWC structures at the MSCRS. All the above processes facilitate soil nutrient export out of the system, which in turn influence the measured soil fertility states of the terraces over time.

The performance of the SWC structures depends on not only appropriate design and construction quality of the structures but also on their suitability for specific site conditions. It was reported that level structures have better performance, while graded structures induce higher soil loss than cultivation without SWC (Herweg and

Ludi 1999). On the other hand, level structures particularly at lower terrain positions are prone to water logging, while graded structures have no such problems (Herweg and Ludi 1999). As discussed above, among the different cause of soil nutrient loss, farmland terracing impacts only on soil and soil nutrient loss through erosion, while other factors still continue to remove soil nutrients. However, with the development of level structures, soil loss through water erosion was considerably reduced (Gebremichael et al. 2005; Herweg and Ludi 1999).

Generally, soil nutrient loss was small while some gain was also evident. The analysis indicates that farmland terracing plays an important role not only in reducing physical soil loss but also in retaining the nutrients. The negative soil nutrient balance could be due to the continued nutrient removal through crop harvest and also partly by soil erosion, as it is difficult to completely stop erosion through terracing (Herweg and Ludi 1999). Without terraces, the soil nutrient status would not be as measured in this study with the continued traditional cultivation practices.

5.4 Summary and conclusions

Terracing is one of the most widely adopted practices. Despite various controversies on the merits and performance of terracing, inadequate empirical evidence exists concerning the role of terracing on soil fertility. The purpose of this study was to analyze impact of farmland terracing in maintaining soil fertility and evaluated variability in its performance within a terrace, across terrace age and at different terrain position. The study was conducted in MSCRS. A total of 48 composite soil samples were collected from 16 plots representing four terrain slope categories (3-5%, 5-8%, 8-15% and 15-30%), three positions within a terrace and each in four replicates. The soil samples were analyzed for texture, pH, EC, OC, av. P, TN, exchangeable bases, CEC and bulk density while soil survey data of 1983 (Weigel 1986) were used as baseline data. The soil laboratory results were statistically tested using analysis of variance (ANOVA).

The results reveal that SWC measures led to clear biophysical changes such as terrain modification, improvement of soil depth, stability of active gullies and stream banks and development of bench terraces. Soil properties such as pH, EC, OC, CEC, Na^+, K^+ and texture showed statistically significant differences across slope of the terrain. Soil pH and exchangeable bases increased with decrease in slope. The increases were due to erosion and leaching of soluble salts from the upper slope and accumulation at the down-slope terrain positions (Chen et al. 1997; Olarieta et al. 2008). Higher soil OC, TN and av. P contents were observed on terraces located on moderately steep slopes. Hence, the terraces received higher organic matter input from the non-arable areas. Significant soil texture differences across the terrain, which indicates that terracing does not completely prevent soil texture gradients.

Unlike in other studies (Dercon et al. 2003; Gebermichael et al. 2005; Vancampenhout et al. 2006), the topsoil physico-chemical properties except bulk density did not show significant differences within a terrace. With development of bench terraces, incoming runoff was uniformly distributed within a terrace, which reduced soil fertility gradients. The mid-terrace position had a significantly higher bulk density (0.4 gm/cm^3) than the other positions of the terraces. This can be attributed to balanced soil aggregate deposition, which resulted soil particles packing (Keller and Håkansson 2010).

Comparison of the 1983 and the current soil survey data revealed nearly stable soil fertility status with very slight changes. Accordingly, pH and TN improved slightly, while OC, av. P, exchangeable bases and bulk density showed a slightly declining trend. The negative balance of some soil nutrients could be due to continued nutrient removal through crop harvest and due to the fact that terracing did not completely stop erosion. The smaller negative balances and only slight improvement in some nutrients indicate that farmland terracing reduced not only soil loss but also nutrient loss. In general, terracing had a number of advantages with respect to reducing soil and soil nutrient loss through erosion; however, terracing alone does not maintain soil fertility. In order to improve soil fertility, terracing should be supplemented by appropriate organic and inorganic fertilizer application according to the site-specific fertility level. Therefore, in this study the following can be concluded concerning the impact of farmland terracing on soil fertility maintenance:

i. Due to regular maintenance and sedimentation, terraces develop to bench terraces, and grasses grown on the terrace wall increased its stability.
ii. With development of bench terraces, topsoil fertility gradients were remarkably minimized, but care should be taken in the interpretation of the above statement

because soil volume and nutrient storage gradients exist within a terrace due to soil depth differences developed at the earlier stage of terrace.

iii. Performance of terracing to reduce soil erosion and fertility vary with terrain. Terracing was more effective in maintaining soil fertility on up to strongly sloping lands (<15% slope).

iv. Terracing reduced soil erosion and soil nutrient loss. This was manifested through stable soil fertility status with slightly positive and negative changes with time. However, terracing alone does not sustain soil fertility, as fertility loss is not only through erosion and also terracing cannot fully halt erosion.

6 PERFORMANCE OF FARMLAND TERRACES IN MAINTAINING CROP PRODUCTIVITY

6.1 Introduction

Various measures have been taken by the Ethiopian government to circumvent the problem of low agricultural productivity due to high erosion and poor soil fertility. The measures include agricultural extension services focusing on utilization of agricultural inputs such as chemical fertilizer and improved seed (Belay and Abebaw 2004), and promotion of soil and water conservation (SWC) (Amsalu and de Graaff 2007; Nyssen et al. 2007; Bingxin et al. 2010). However, the intervention programs are challenged by different factors. For instance, the extension programs are unlikely to succeed in an environment where fertilizer use is much below the soil nutrient lost through crop harvest and soil erosion (Bingxin et al. 2010). The SWC program is mainly constrained by limited adoption and continuity issues (Amsalu and de Graaff 2007). SWC intervention has been widely implemented in the northern highlands, which cover large areas (Herweg and Ludi 1999; Amsalu and de Graaff 2007). Among the different SWC interventions, contour terracing has been widely implemented on farmlands.

However, there are different opinions concerning the advantages of farmland terracing. Farmland terracing has been known to modify terrain by reducing slope angle and length at farm level and changing slope shape at the micro-watershed level, thereby decreasing soil erosion, and enhancing hydrology and crop productivity (Shiferaw and Holden 1999; Badege 2001; Sonneveld and Keyzer 2003; Nyssen et al. 2007). In contrast, some researchers and farmers have criticized terracing for its negative effects such as yield and fertility gradients within a terrace, for harboring rodents thus resulting in crop yield loss, for reducing farm size, and for creating problems for oxen-drawn plowing (Herweg and Ludi 1999; Dercon et al. 2003; Vancampenhout et al. 2006; Amsalu and de Graaff 2007; Nyssen et al. 2007).

The aim of this chapter is to provide a quantitative analysis of the impact of farmland terracing in improving and/or maintaining crop yields, and to evaluate terrace performance across terrace age, within a terrace and across the terrain. The results will provide empirical evidence concerning the performance of farmland terracing with respect to crop production and productivity.

6.2 Material and methods

6.2.1 Study area

The study was conducted in the Maybar soil conservation research site (MSCRS), which is located in the Lake Maybar watershed in the sub-humid agro-ecological zone, locally classified as *Dega* (Hurni 1998). *Dega* agro-ecology is characterized by cool, humid highland conditions at altitudes between 2500 and 3200 m a.s.l. (NMSA 1996; Hurni 1998). The area receives bimodal rainfall namely *Belg* and *Kiremt* (NMSA 1996; Hurni 1998; SCRP 2000). The *Belg* (spring) is a first rainy season between April and May, while *Kiremt* (main) is the second rainy season between July and September. Due to the bimodal rainfall, the area has two cropping seasons (Herweg and Ludi 1999). However, in some cases there is only one cropping season when the *Belg* rainfall fails. The main crops are cereals and pulses and include wheat (*Triticum* spp), emmer wheat (*Triticum* spp), horse bean (*Vicia faba*), field pea (*Pisum sativum*), barley (*Hordeum* spp), maize (*Zea mays*) and teff (*Eragrostis tef*) (SCRP 2000). For further details of the study area see Chapter 5.

6.2.2 Plot selection and sampling

Crop yield data were obtained from the project coordination office in Addis Ababa after official communication with the Sirinka Research Center and Amhara Regional Agricultural Research Institute (ARARI). Grain and biomass (straw and grain cover) yield data collected by MSCRS were used in this analysis. In the establishment phase, the project collected baseline data, constructed SWC structures and established different setups such as field plots, test plots, and meteorological and river gauge stations. The baseline data are based on soil surveys while an appraisal was conducted for the land degradation status. The field plots were established for runoff and erosion monitoring, soil conservation experiments and crop yield monitoring (Herweg and Ludi 1999; SCRP 2000). The project identified 40 fixed plots (Figure 6.1) to monitor the yields of major crops. The analysis in this study is based on the yield data of the fixed plots.

Terracing was made possible by the technical and financial support of the program (SCRP), whereas cultivation is based on farmers' traditional practices that involve oxen-drawn cultivation, hand weeding and no or very limited fertilizer application (Herweg and Ludi 1999; SCRP 2000). Crop selection and management were based on individual farmer decisions. Yield monitoring was done for barley (*Hordeum* spp), wheat (*Triticum* spp), maize (*Zea mays*), teff (*Eragrostis tef*), emmer wheat (*Triticum dicoccum*), field pea (*Pisum sativum*), horse bean (*Vicia faba)* and lentil (*Lens culinaris*). Cereals and pulses are mainly sown in the *Belg* and *Kiremt* seasons, respectively. Barley and emmer wheat are mainly cultivated during the *Belg* season, and teff and field pea in the *Kiremt* season. Maize is sown during the *Belg* season and harvested after the *Kiremt*. Thus, yield data of both seasons were used in the analysis. Out of the available data, yields of all crops except lentil were statistically analyzed. As lentil is rarely cultivated, it was excluded in this analysis. This study used yield data of 1995 through 2009 except for the year 2002, when no data were available. In order to compare yield changes across the terrain, the fixed plots were grouped in slope classes by the use of a digital elevation model (DEM) (Figure 6.1). Accordingly, the fixed plots were grouped as gently sloping (3 - 5%), sloping (5 - 8%), strongly sloping (8 - 15%) and moderately steep (15-30%), which is adopted from FAO system of classification (FAO, 2006).

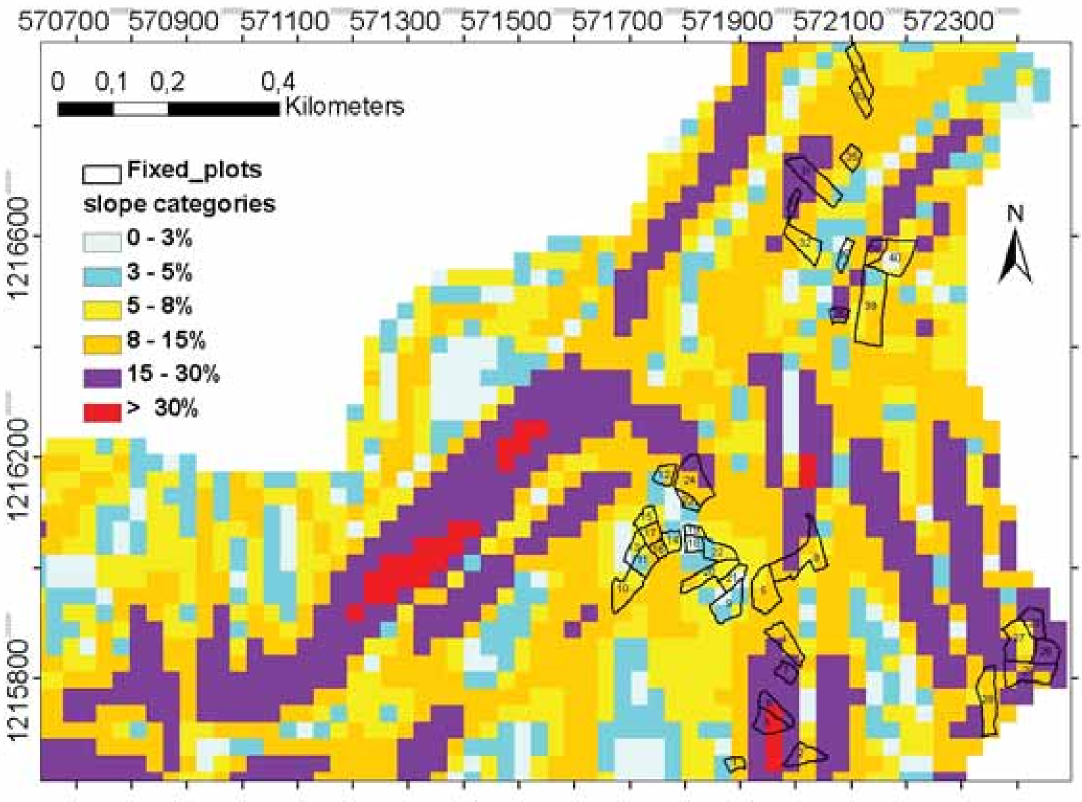


Figure 6.1 Fixed plots with DEM-generated slope map

Crop yield data monitoring has been carried out annually in both cropping seasons on the three terrace positions at randomly selected terraces on the fixed plots. The position on the terrace refers to the relative location of the sample plots between successive terraces. The size of a sampling plot was 4 m^2 (2 m x 2 m). The plots were located at three positions inside the terrace, i.e., low-terrace (A), mid-terrace (B) and up-terrace (C) positions (Figure 6.2). For design of the sampling plots see Chapter 5.

Figure 6.2 Terrace positions (A) low-, (B) mid-, and (C) up-terrace

It is important to note that each fixed plot may or may not be cultivated in both seasons depending on the farmer plans and climatic conditions, particularly the adequacy of the *Belg* rain. As a result, data size varies with year and season. As the total numbers of fixed plots were 40, thus the maximum possible samples in a season were 120, as sampling was on three terraces positions (low-, mid-, up-). However, in the analysis years 1995 to 2009, the maximum number of fixed plots cultivated in a season was 37, i.e., a total of 111 samples. Yield gradient calculations were done in ton per hectare ($t\ h^{-1}$). However, the calculation did not consider the area lost due to the terrace construction despite the fact that measurement in this study showed 2% to 12% of farm land occupied by terraces whereby, on average, 6% of the land comes out of crop production. Similarly, other studies indicated that 10% to 15% of land lost by terracing depending on slope (Herweg and Ludi 1999; Vancampenhout et al. 2006). Nevertheless, this does not affect the plots yield comparison.

6.2.3 Statistical data analysis

Crop yield is a function of bio-physical factors and management such as soil, climate, inputs, crop rotation, etc. The physical factors are the terracing and the farmers´ practices, while the natural factors are governed by prevailing conditions. Crop selection, rotation and other management practices are based on farmers´ decisions and experience. Thus, the crop yield performance evaluation is an observational study. As a consequence, various known and unknown confounders such as variations in sample sizes across season and year due to farmers´ decisions and other naturally occurring as well as management-based variations are involved. This calls for use of a model that considers these variations and disturbances. Therefore, the yield data were statistically analyzed mainly by a mixed linear model using the statistical software package SAS (Version 9.2). Multiple pair-wise testing was conducted using the Tukey-Kramer adjustment. The mixed model used yield (grain and biomass) as dependent variables, slope of the terrain and terrace position as fixed factors of interest, and age as a covariate. Since the plots are inherently heterogeneous, they were considered as subject effect. Therefore, the interpretation in this analysis is based on the Tukey-Kramer adjustment that used adjusted P values.

A mixed model is defined as:

$$y = X\beta + Z\gamma + \varepsilon \tag{6.1}$$

where y, β, γ and ε are vectors;

y = observation with E(y) = X β ; β = fixed effect; and γ = random effect

X and Z are fixed and random effect model matrices, respectively, in relation to the observation y to β and γ .

Note that a grand mean μ is mostly incorporated through an extra column within 1 in X and a parameter μ in β

The above mixed-effect model assumes that:

- ε and γ are mutually uncorrelated, normally distributed variables with zero expectation

- but covariance of ε and γ could have a general (unstructured) form

Therefore, the explicit mixed liner model for our data is:

$$\begin{pmatrix} y_1 \\ \cdots \\ \cdots \\ y_n \end{pmatrix} = \begin{pmatrix} 1 & slope_1 & position_1 & age_1 \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ 1 & slope_n & position_n & age_n \end{pmatrix} \times \begin{pmatrix} \mu \\ \beta_{slope} \\ \beta_{position} \\ \beta_{age} \end{pmatrix} + \begin{pmatrix} z_1 \\ \cdots \\ \cdots \\ z_n \end{pmatrix} \times ploteffect + \begin{pmatrix} \varepsilon_1 \\ \cdots \\ \cdots \\ \varepsilon_n \end{pmatrix} \tag{6.2}$$

where y_i = yield at plot i (i = 1, ..., n) with a specific terrain slope, terrace position and age
β = (β_{slope}, $ß_{\text{position}}$, $ß_{\text{age}}$) fixed effects
γ = random plot effect.

6.3 Results and discussion

6.3.1 Impact of farmland terracing on crop yield across terrain

Grain and biomass yield data were collected and analysed separately. But as the results follow similar trend, the presentation of the grain and biomass yield analysis results and the discussion are combined. The analysis revealed that most crops showed insignificant yield differences across the terrain. Among the seven crop types analyzed, only the grain yields of barley (P = 0.01), field pea and emmer wheat (P = 0.05) showed significant differences across the terrain. Similarly, barley and field pea biomass showed higher significant (P = 0.05) differences, and emmer wheat biomass showed only marginal (P = 0.1) differences (Table 6.1). Both grain and biomass yield of most crops except wheat tends to decrease in the upslope direction.

Although the yield tends to decrease in the upslope direction, the pair-wise comparison shows a nonlinear gradient across the slope of the terrain. For example, unlike other crops, a very low wheat yield (biomass and grain) was observed on gently sloping (3-5%) terrain; yields were over 50% lower than the average values. Other crops showed higher yields on gently sloping (3-5%) and sloping (5-8%) terrain. Also, the highest maize, emmer wheat and horse bean yield was measured on gentle slopes (3-5%), while the highest barley, wheat, teff and field pea yields were measured on sloping (5-8%) terrain. However, the yield differences between gently sloping and sloping terrain were very small except in the case of wheat. The comparison of yields on strongly sloping (8-15%) and moderately steep slopes (15-30%) showed an irregular yield pattern that varied with crop type. Barley, wheat, maize and field pea yields on moderately steep slopes were higher than on the strongly sloping terrain. Although mean wheat yield on 3-5% slope terrain position was considerably smaller than those on other positions (5-8%, 8-15% and 15-30%), differences were statistically non-significant, i.e. non-significant F value. This is due to small sample size (onlay 6 samples at the 3-5% slope terrain position) and the large standard error (Figure 3).

Table 6.1 Crop yield (t ha^{-1}) on terraces across terrain

	Biomass yield (t ha^{-1}) by slope (%)				
Crop type	3-5%	5-8%	8-15%	15-30%	F^{-Value}
Barley	4.6^{dbd}	4.7^{bd}	2.9^{d}	4.3	3.62**
Wheat	1.3	4.3	3.0	4.0	2.01^{ns}
Maize	6.5	5.0	4.2	5.3	1.06^{ns}
Teff	2.8	4.1	3.5	2.7	1.45^{ns}
Emmer wheat	5.0^{cdc}	2.6^{dd}	3.4^{d}	2.9	2.54*
Field pea	2.9^{ddd}	3.9^{bd}	1.6^{d}	2.4	0.09**
Horse bean	3.7	2.5	2.9	2.8	0.42^{ns}

	Grain yield (t ha^{-1}) by slope (%)				
Crop type	3-5%	5-8%	8-15%	15-30%	F^{-Value}
Barley	2.3^{dbd}	2.2^{bd}	1.3^{d}	1.9	4.40***
Wheat	0.3	1.6	1.2	1.5	1.63^{ns}
Maize	2.0	1.8	1.6	1.8	0.15^{ns}
Teff	1.2	1.8	1.4	1.2	1.66^{ns}
Emmer wheat	2.4^{ddb}	1.4^{dd}	1.5^{d}	1.2	2.89**
Field pea	0.7^{ddd}	1.9^{bd}	0.6^{d}	1.0	3.85**
Horse bean	2.2	1.2	1.6	1.5	0.78^{ns}

Note: *The letters a, b, c and d indicate that biomass and grain yield of a given crop type was different (a) at P = 0.01, (b) at P = 0.05, (c) at P = 0.1 and (d) non-significant as compared with the subsequent slope categories at P < 0.1 (Tukey-Kramer).*

F^{value} is *** significant at P = 0.01, ** significant at P = 0.05, * significant at P = 0.1, and ^{ns} non-significant.

The non-significant yield differences across the terrain may indicate that terracing reduced the impact of soil erosion on soil fertility and thereby on crop productivity. The rate and degree of soil erosion largely depends on the slope of the land, which could result in crop productivity gradients (Gebremichael et al. 2005; Nearing et al. 2005; Vancampenhout et al. 2006; Nyssen et al. 2007; Olarieta et al. 2008). However, the current analysis shows that the gradient was not significant across the terrain, which suggests a positive impact of terracing.

Even though terracing contributes to reducing soil erosion, it also has negative impacts on crops sensitive to certain effects, such as water-logging. This negative impact of terracing has been observed with respect to wheat. The lowest wheat yield on gently sloping terrain could partly be attributed to the negative effects of terracing, in this case water-logging. Herweg and Ludi (1999) reported that level structures (e.g., level bund, level terraces and level *Fanya Juu*) could result in water-logging problems at lower terrain positions. Other studies also show that water-logging critically limits wheat yield (Olgun et al. 2008; Ghobadi and Ghobadi 2010).

The slight yield gradient across the terrain, i.e., yield decrease towards the upper slope position, may be a result of the erosion before terracing. Although terracing reduces soil erosion and nutrient loss by changing slope angle, length and shape, the effect of erosion before the terracing remains for a long time after the terracing (Nearing et al. 2005; Vancampenhout et al. 2006; Nyssen et al. 2007; Olarieta et al. 2008). The yield decrease towards the upslope position of the terrain is likely related to soil depth differences resulting from soil erosion and deposition processes before the intervention (see Chapter 5). Soil depth influences water and nutrient storage. Studies indicate that on cultivated land, erosion induces soil depth gradients across the slope of the land, which in turn result in soil fertility and crop productivity variation (Nearing et al. 2005; Vancampenhout et al. 2006; Nyssen et al. 2007).

Soil washed from upper slopes is partly deposited down-slope, as the runoff energy is reduced, which in turn results in soil depth and nutrient storage gradients at micro-watershed level (Chen et al. 1997; Nearing et al. 2005). Thus, the terraces on the lower slope positions were deeper than those on the upper slopes, which in turn influenced overall plant-available nutrients (Calviǹo and Sadras 1999; Tesfaye and Walker 2004). Moreover, lands situated on lower slope positions were less affected by erosion. As a result, this land had deeper soil even before terracing (Gebremichael et al. 2005; Nyssen et al. 2007). This also applies to the soils in this study (Chapter 5).

6.3.2 Impact of farmland terracing on crop yield within a terrace

The analysis showed significantly higher yield (grain and biomass) differences within a terrace even after the Tukey-Kramer adjustment. Crops on low-terrace (A) positions had better stands and higher density than those on the mid- (B) and up-terrace (C) positions.

Pair-wise comparisons showed a similar trend in most crops, where yields decreased towards the up-terrace position. However, the differences among crop types were nonlinear (Table 6.2 and Figure 6.3). Accordingly, the grain yields of five crops (barley, maize, teff, field pea and horse bean) significantly ($P < 0.02$) decreased towards terrace position C. Similarly, all crops except wheat had significantly ($P \leq 0.002$) higher biomass yield on the terrace position A. The biomass on average measured 4.2 t h^{-1}, 3.5 t h^{-1} and 3.0 t h^{-1} on terrace position A, B and C, respectively (Table 6.2). Crop yields without significant differences also tended to decrease towards position C. Although terrace position B had higher grain yields for all crops except field pea than terrace position C, the differences were statistically insignificant for all crops except teff and horse bean. On the other hand, terrace position B had significantly higher barley, wheat, teff and horse bean biomass than position C, while the biomass of the other crops showed non-significant differences. Generally, low yields were measured on terrace position C for most crops except field pea, and the magnitude of the differences varied with crop type (Table 6.2).

Table 6.2 Average crop yield (t ha^{-1}) on three terrace positions

Crop	Grain yield (t ha^{-1})				Biomass yield (t ha^{-1})			
	A	B	C	F^{-Value}	A	B	C	F^{-Value}
Barley	2.20^{aa}	1.88^{d}	1.61	44.88^{***}	4.8^{aa}	4.0^{b}	3.4	13.82^{***}
Wheat	1.17	1.24	1.03	0.76^{ns}	3.4^{db}	3.3^{c}	2.8	2.51^{*}
Maize	2.51^{aa}	1.64^{d}	1.24	17.07^{***}	6.7^{aa}	4.9^{d}	4.1	11.80^{***}
Teff	1.60^{ba}	1.52^{b}	1.16	13.59^{***}	3.6^{da}	3.4^{a}	2.8	9.17^{***}
Emmer wheat	1.84^{db}	1.55^{d}	1.44	5.04^{*}	4.0^{ba}	3.4^{d}	3.0	7.01^{***}
Field pea	1.28^{ab}	0.92^{d}	0.92	5.99^{***}	3.3^{aa}	2.4^{d}	2.4	9.11^{***}
Horse bean	1.89^{ba}	1.67^{b}	1.37	9.44^{***}	3.4^{da}	3.1^{b}	2.6	8.25^{***}

Note: *Terrace positions: A= low-, B= mid- and C = up-terrace. See Table 6.1for abbreviations and superscripts.*

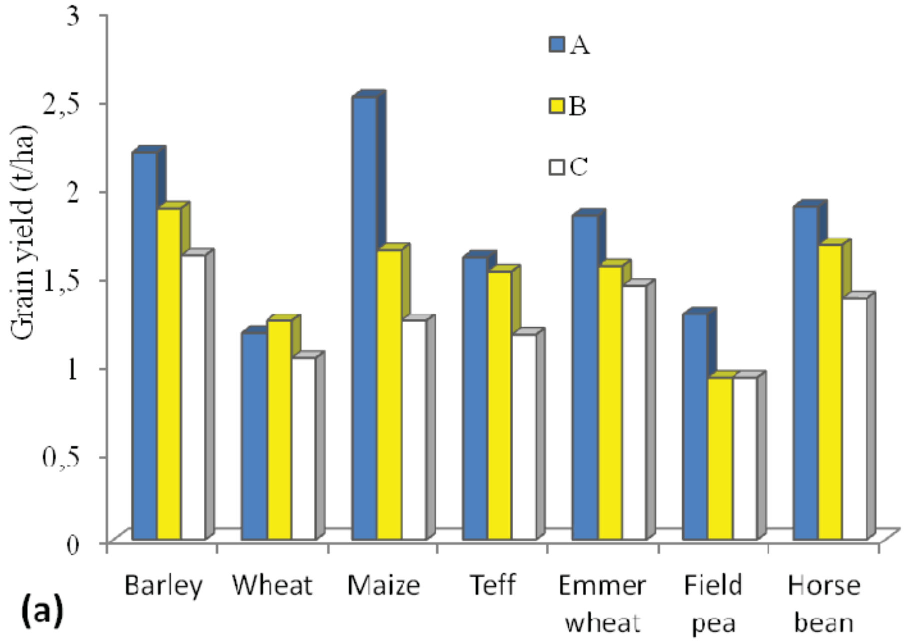
Higher grain yield differences were observed between position A and C than between position A and B or between position B and C (Table 6.3). The overall grain yield on the terrace position A was 0.53 t ha^{-1} higher than terrace position C; however, the differences varied with crop type (Figure 6.3a). The grain yield differences between position A and C varied from 0.14 t ha^{-1} in case of wheat to 1.27 t ha^{-1} in the case of maize. Similarly, the grain yield differences between position A and B varied from nil in case of wheat to 0.87 t ha^{-1} in the case of maize, while between position B and C yields ranged from 0 t ha^{-1} in the case of field pea to 0.4 t ha^{-1} in the case of maize

(Table 6.3). Generally, average grain yield differences were 0.53 t ha^{-1} between position A and C, 0.3 t ha^{-1} between position A and B, and 0.24 t ha^{-1} between position B and C. Higher grain yield differences were observed in case of maize, while the differences for wheat were the lowest. The biomass yield gradient within a terrace followed the same trend as that of the grain yield (Figure 6.3b). The highest biomass difference was between terrace position A and C followed by between position A and B and between position B and C, respectively (Table 6.3). Biomass and grain yield showed similar differences within a terrace (Figure 6.3).

Table 6.3 Crop yield differences (t ha^{-1}) between terrace positions

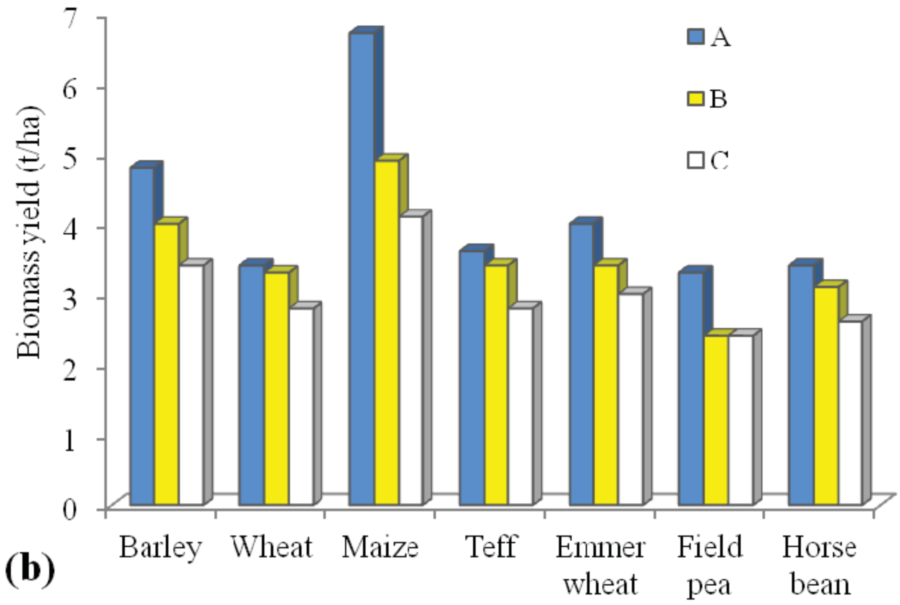
Crop	Grain yield differences (t/ha)			Biomass yield differences (t/ha)		
	A - B	A - C	B - C	A - B	A - C	B - C
Barley	0.32	0.59	0.27	0.8	1.4	0.6
Wheat	-0.07	0.14	0.21	0.1	0.6	0.5
Maize	0.87	1.27	0.40	1.8	2.6	0.8
Teff	0.08	0.44	0.36	0.2	0.8	0.6
Emmer wheat	0.29	0.40	0.11	0.6	1.0	0.4
Field pea	0.36	0.36	0.00	0.9	0.9	0.0
Horse bean	0.22	0.52	0.30	0.3	0.8	0.5
Average	*0.30*	*0.53*	*0.24*	*0.7*	*1.1*	*0.5*

Note: *See Table 6.2 for abbreviations*



Note: Terraces positions: A = low-, B = mid- and C = up-terrace position

Figure 6.3 Grain (a) and biomass (b) yield (t ha^{-1}) on the three terrace positions



Note: Terraces positions: A = low-, B = mid- and C = up-terrace position

Figure 6.3 continued

6.3.3 Impact of terracing on crop yield across terrace age

In this analysis, in order to avoid the effect of yield variation on the overall crop yield, the comparison is based on relative yield. The relative yield for each measurement was calculated as: relative yield = [grain yield/biomass yield]*100 (Hay 1995). The relative yield of all crops measured in all plots in every year under consideration is termed as ‘all crops observed relative yield’. The analysis revealed very high variations ranging from 4% for field pea to 83% for wheat (Figure 6.4b). On the other hand, the average values of all crops for each year were almost stable with only a very slight increase (Figure 6.4b), which varied from 32% in 1998 to 49% in 2009 (Figure 6.4b). The maximum and minimum mean relative yield of all crops showed wide variation (Table 6.4). Accordingly, the yearly minimum values ranged from 4% to 21%, while the maximum values were from 63% to 77% (Table 6.4). The analysis showed high fluctuations across the year without a regular trend. As a whole, the yields tended to increase slightly with terrace age (Figure 6.4). This shows that grain and biomass yield across age of the terraces followed a nonlinear trend with very high standard deviations (Figure 6.4a). The irregular yield change could be due to other factors such as rainfall variability rather than to the influence of terracing on plant nutrition (Hay 1995). For example, in 1998, an abrupt yield decrease was observed.

Table 6.4 All crops minimum, maximum and mean relative yield over time (%)

Year	1995	1996	1997	1998	1999	2000	2001
Max.	73	64	68	50	83	77	77
Min.	4	7	12	11	21	10	21
Mean	46	41	44	32	46	38	48

Year	2003	2004	2005	2006	2007	2008	2009
Max.	70	67	63	67	67	65	73
Min.	6	22	22	22	18	7	18
Mean	47	45	45	45	46	42	49

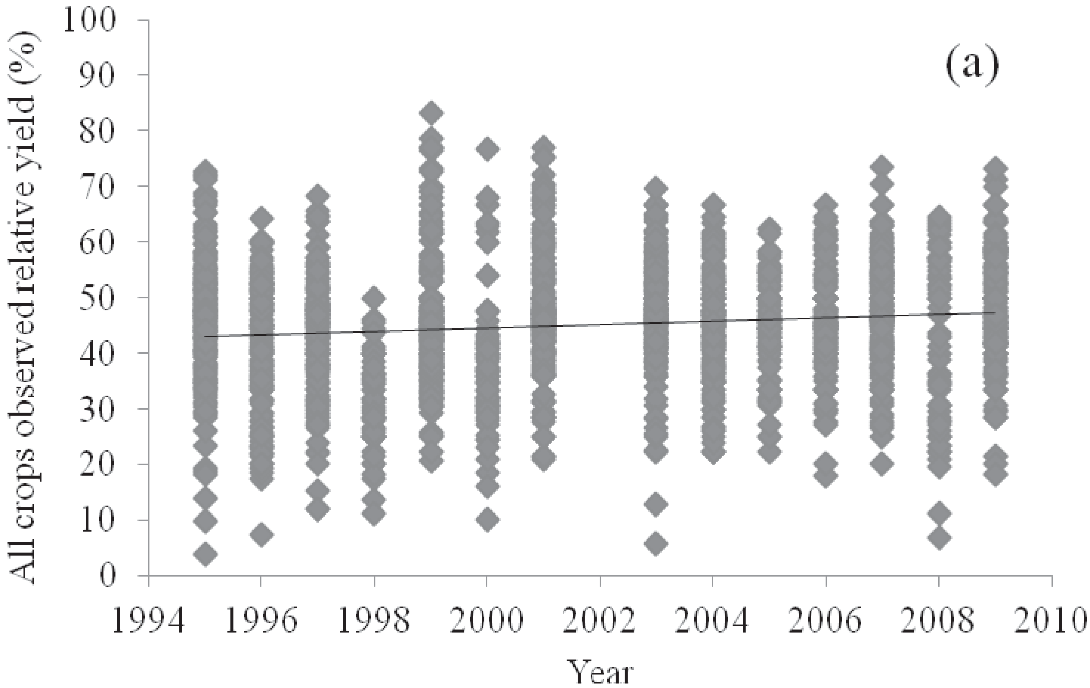


Figure 6.4 Relative yields across terrace age: (a) All crops observed relative yield, and (b) All crops mean relative yield

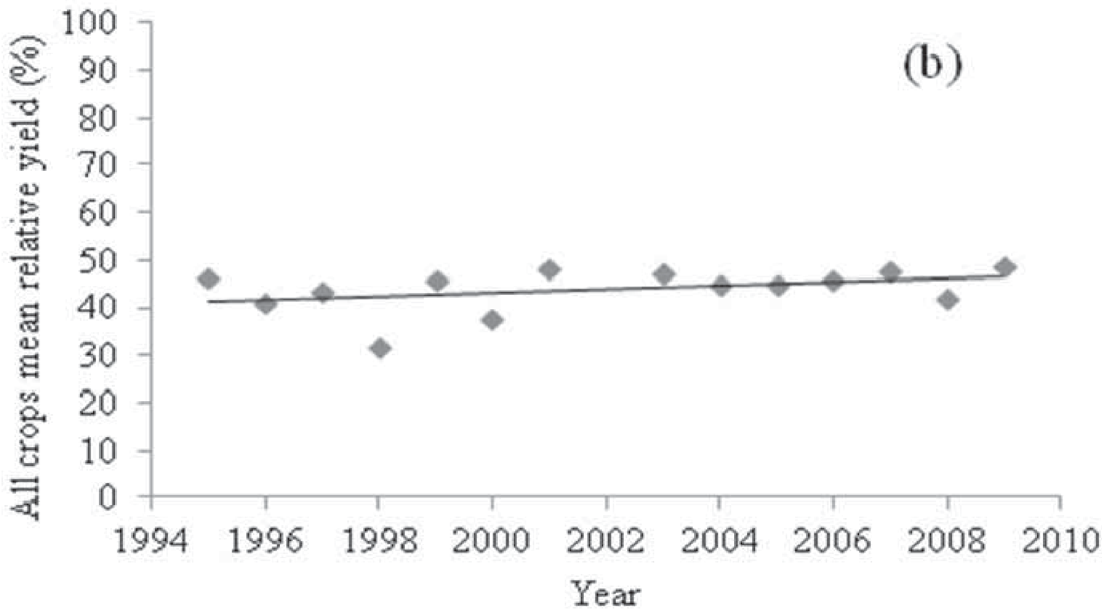


Figure 6.4 continued

Comparisons of grain yield at different terrace age considering crop types showed variations with high standard deviation (Figure 6.5). For example, the average legumes (horse bean and field pea) yield showed an increasing trend, while cereals showed a nonlinear pattern. Barley, teff and emmer wheat slightly decreased, while wheat and maize tended to increase. However, in general, crop yield showed only very slight increases and decreases, which indicates stable conditions. Similarly, Herweg and Ludi (1999) reported that crop yields remained stable on the same plots between 1986 and 1989.

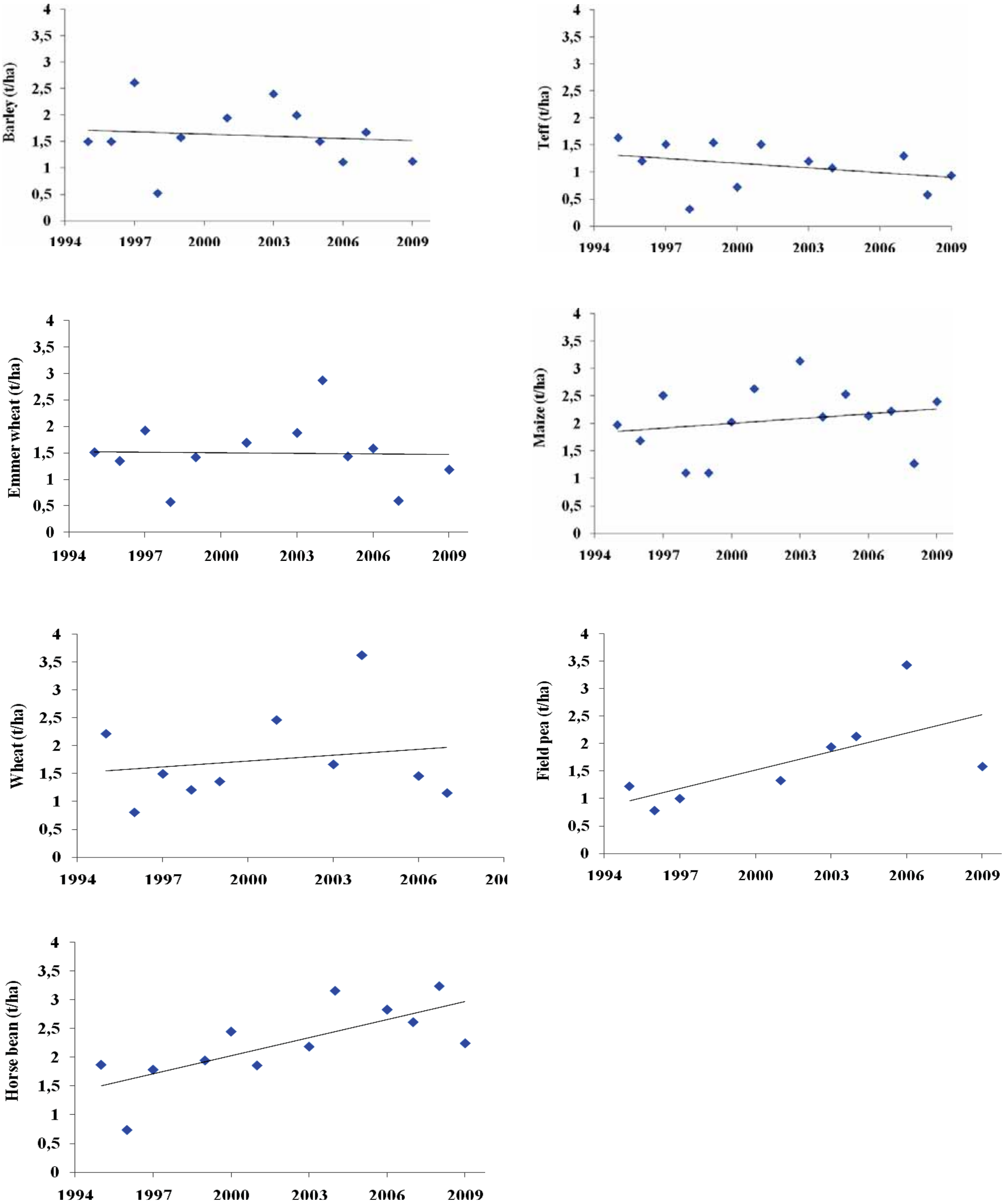


Figure 6.5 Different crops grain yield across terrace age

This indicates that terracing contributed to stable soil fertility (section 5.3.4) and crop yields across time. The stable yield in spite of the continued soil nutrient removal through harvesting, reduced fallowing and no or very limited fertilizer application (chemical and organic) can be attributed to the impact of terracing, which reduced soil erosion. Agricultural practices in Ethiopia in general and in the study area in particular are still traditional. They are characterized by low or no chemical fertilizer utilization, minimal crop residue retention and limited fallowing (Herweg and Ludi 1999; Omiti et al. 1999; Haileslassie et al. 2005). Like other highlands in the country, fallowing is greatly reduced and in some cases completely abandoned. The highlands receive bimodal rainfall, and as a result cultivating land twice a year is common (Hurni 1998; Herweg and Ludi 1999; SCRP 2000). In the study area, limitation of arable land and the food demand for the rapidly growing population has forced farmers to cultivate land twice a year. Thus, fallowing is mostly only between two cropping seasons rather than over years.

Therefore, slight yield gradients across the terraces age indicate that terracing has contributed to sustainable production by preventing erosion, which would have resulted in severe degradation and yield loss. Discussions with the local farmers confirmed this. The farmers reported that before terracing considerable farmland on the very steep slopes was abandoned as the land became unproductive. This land was then terraced, fallowed for some time and then used for crop production. This clearly shows that terracing positively impacted crop production. The stable crop yield despite the continued nutrient removal through crop and residue harvest (Omiti et al. 1999; Haileslassie et al. 2005) also indicates that terracing played important role and that otherwise yields could have significantly decreased. It can be concluded that terracing has helped to achieve sustainable production; however terracing alone may not improve agricultural productivity.

6.4 Summary and conclusions

This study analyzed the performance of terracing with respect to crop productivity, and evaluated the yield differences across the slope of the terrain, within a terrace and across terrace age. Yield data (grain and biomass) of seven crop types, namely barley, maize, wheat, emmer wheat, teff, horse bean and field pea collected between 1995 and 2009 from 40 fixed plots on three terrace positions (low-, mid- and up-) were evaluated. The plots were grouped based on DEM-generated slope classes as gently sloping (3-5%), sloping (5 - 8%), strongly sloping (8 - 15%) and moderately steep (15-30%). The data were statistically analyzed in SAS taking grain and biomass yield as dependent variables; slope of the terrain and terrace position as fixed factors, year as covariate, and plot as a subject effect.

Generally, yield (biomass and grain) showed insignificant differences across the terrain with a tendency to decrease with slope increase. Nevertheless, few crops showed marked differences. For example, barley yield significantly decreased with slope increase, while field pea showed higher yields on the sloping terrain position. The insignificant yield differences for most crops across the terrain imply that terracing reduced soil erosion and nutrient translocation, thereby reducing significant yield loss in erosion zone. The tendency of yield decrease across the terrain could be due to the soil erosion before terracing that influenced soil depth, thereby affecting nutrient and water storage capacity. The effect of previous erosion depends on the crop type (Calviǹo and Sadras 1999; Tesfaye and Walker 2004).

On the other hand, biomass and grain yield of all crops except wheat significantly decreased from low-terrace position towards up-terrace position. This is in line with other studies (Herweg and Ludi 1999; Dercon et al. 2003; Vancampenhout et al. 2006; Nyssen et al. 2007). The studies relate the differences to topsoil fertility gradients however, in this study there were no such variations (Chapter 5). Thus, the variation could be due to the soil depth gradient that in turn influenced nutrient and soil-water storage.

Crop production in the study area applies only limited fertility improvement measures, and fallowing is reduced. This indicates that terracing reduced soil and nutrient loss through erosion, otherwise yields would have been significantly reduced under the continued nutrient export through harvest. The only slight yield change after terracing indicates that terracing alone does not improve soil fertility and thereby crop production. Thus, farmland terracing should be supplemented by other agricultural packages such as use of soil fertility amendments and other agronomic practices. In this study the following is concluded:

i. As terraces develop to bench terraces, no significant yield differences across the slope of the terrain. However, the tendency of slight yield decrease across the terrain could be attributed to erosion/deposition processes before the measure. This implies that a longer time could be necessary to substantially reduce the impact of erosion on crop production and productivity through terracing. This calls for site-specific, soil fertility maintaining interventions to reduce the variations.
ii. The lowest yield of some crops (i.e., wheat) on the lower terrain position can be attributed to the impact of terracing on crops sensitive to water-logging. Hence, it is advisable to cultivate crops appropriate to the respective terrain positions.
iii. The magnitude of the yield gradient within a terrace decrease over time. However, management plans should consider the differences within a terrace to eliminate the yield variations.
iv. Generally, most crop yields showed stable condition with age of terraces. There was no change in fertilizer use, and nutrient removal through harvest continued. This indicates that terracing helped to maintain crop production and productivity. However, it can be assumed that terracing alone does not increase productivity. Therefore, terracing should be complemented by fertility improving interventions.

7 PERFORMANCE OF EXCLOSURE IN RESTORING SOIL FERTILITY

7.1 Introduction

Wello is one of the most severely degraded parts of the Ethiopian highlands (Herweg and Ludi 1999; Tekle 1999). It is densely populated and has rugged topography dominated by hills, mountains, escarpments and gorges (Tekle 1999; CSA 2008). The area is also characterized by low agricultural productivity (Weigel 1986; Herweg and Ludi 1999; SCRP 2000). Cultivation and grazing activities have spread to steep landscapes at the expense of forest and natural vegetation (Tekle 1999). As a consequence, land degradation, particularly erosion and soil quality deterioration, has increased at an alarming rate (Tekle 1999; Descheemaeker et al. 2010).

Exclosure is one of the widely employed interventions to rehabilitate degraded lands, restock biodiversity and restore soil fertility (Asefa et al. 2003; Descheemaeker et al. 2006; Mekuria et al. 2007). However, controversial results have been reported on the impact of exclosure in restoring resource bases of degraded lands especially with respect to soil fertility. For example, over 100% dry matter increase (McIntosh et al. 1997), up to 70% topsoil organic carbon (OC) increase (Mekuria et al. 2007) and over 10% topsoil total nitrogen (TN) increase (McIntosh et al. 1997; Mekuria et al. 2007) following exclosure were reported. Conversely, others reported insignificant soil OC and TN change in exclosures (Richter et al. 1999; Eshatu 2004; Kalinina et al. 2009).

Moreover, farmers perceive exclosure negatively as it creates competition with grazing land, which forced them to reduce livestock and thereby negatively affect their livelihood (Mekuria et al. 2011). Soil fertility self-restoration on degraded land through exclosure is also affected by various factors such as time, terrain steepness and microclimatic conditions (Fu et al. 2003; Descheemaeker et al. 2009; Mekuria et al. 2011; Kalinina et al. 2009). In spite of the controversies and differences in soil fertility restoration, exclosure has been widely implemented in many parts of the Ethiopian highlands including Wello. Moreover, exclosure interventions followed similar approach and management practices regardless of differences in terrain steepness, agro-ecological zones and age of the exclosures. Therefore, in this chapter we analyzed the impact of exclosure on soil fertility restoration and examined the restoration rate across different exclosure ages, agro-ecological zones and landscape positions.

7.2 Material and methods

7.2.1 Study area

The study was conducted in the Gubalafto district (*Wereda)* of the North Wello zone, Amhara National Regional State. The district is located between 11°35' and 12°00' north latitude and 39°14' and 39°48' east longitude (Figure 7.1). It covers 990km² and altitudes vary between 1300 and 3500 m a.s.l. The geology of the area is dominated by Cenozoic volcanic rocks, mainly Ashangi and Aiba basalts (Tefera et al. 1996).

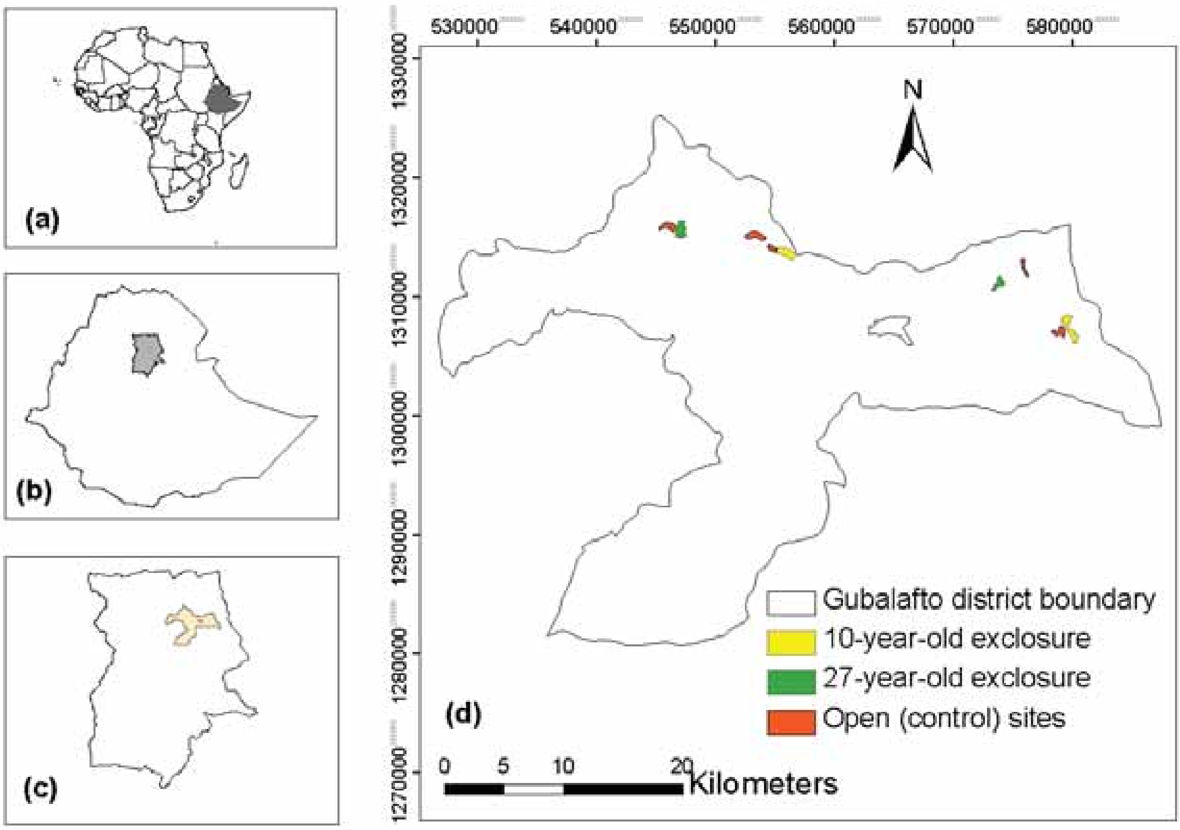


Figure 7.1 Location of study area: (a) Ethiopia in Africa, (b) Wello in Ethiopia, (c) Gubalafto district in Wello, and (d) Sample sites in Gubalafto district

Like most parts of Wello, Gubalafto district is characterized by rugged topography where different landscapes are used for different purposes. Valley floors, plateau and terraces are used for cultivation and settlements, while steep terrains are used for grazing and exclosure, and some areas are waste lands. Gubalafto district is situated within the watershed boundaries of the Abay, Awash, Tekeze and Golina rivers. According to the FAO classification system, the dominant soil types of the area are

Cambisols and Leptosols (FAO 1984). The mean annual temperature and rainfall range from 18°C to 22°C and 680 to 1050 mm, respectively. About 50% of the annual rainfall falls in July and August. May and June are the hottest months and December is the coldest month. Due to the wide climatic and elevation range, Gubalafto district has diversified agro-ecological zone including *Kolla* (warm, semi-arid, lowlands, 130 to 1500 m a.s.l.), *Weyna-Dega* (mild, sub-humid highlands, 1500 to 2300 m a.s.l.), *Dega* (cool, humid highlands, 2300 to 3200 m a.s.l.) and *Wurch* (cold, humid highlands, over 3200 m a.s.l) (NMSA, 1996; Hurni, 1998). The warm (*Kolla*), mild (*Weyna-Dega*), cool (*Dega*) and cold (*Wurch*) agro-ecological zones cover 5.5%, 40.2%, 32.1% and 22.2% of the district, respectively (Figure 7.2).

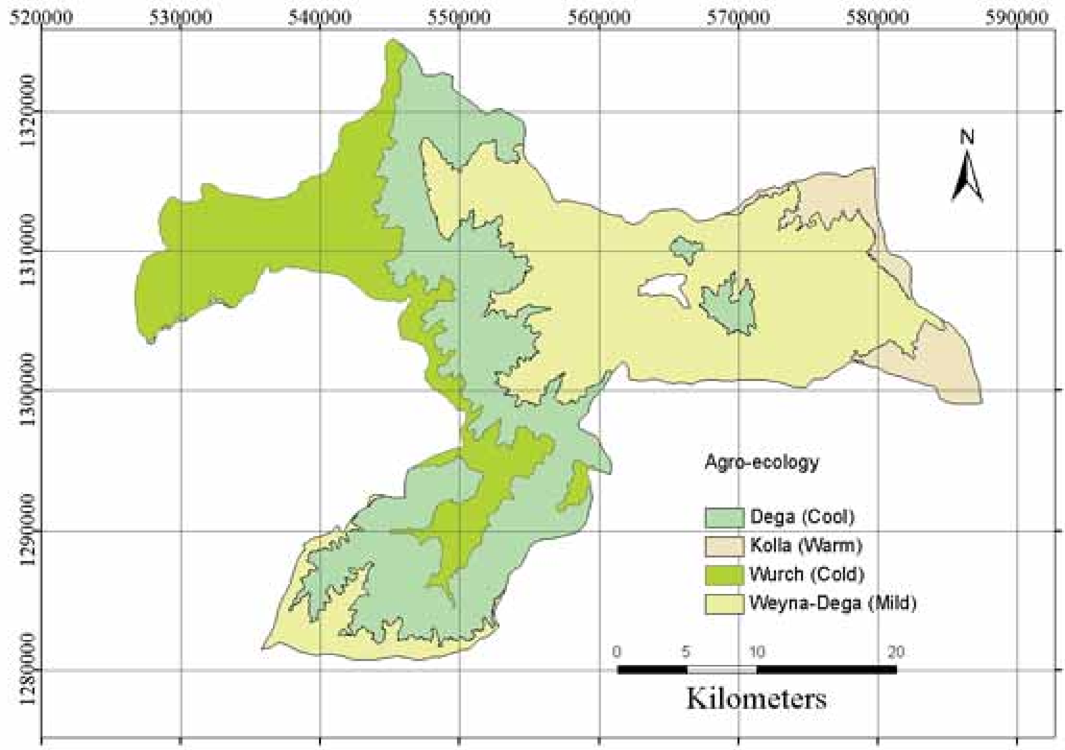


Figure 7.2 Agro-ecological zones of Gubalafto district

In this study, the local agro-ecological zones are translated as given before the bracket. The wider agro-ecological zones of the area favors a broad range of crops such as sorghum (*Sorghum bicolor*), maize (*Zea mays*), teff (*Eragrostis tef*), barley (*Hordeum* spp), wheat (*Triticum* spp), field pea (*Pisum sativum*) and horse bean (*Vicia faba*). A wide range of tree species are found in the district, which have different uses and ecological requirements, e.g., *Acacia saligna*, *Acacia seyal*, *Aloe ferox*, *Eucalyptus camaldulensis, Euclea schimperi* in the mild zone while *Acacia asak*, *Carissa edulis*, *Cupressus lusitanica*, *Erica arborea*, *Eucalyptus globulus*, *Euphorbia abyssinica, Hagenia abyssinica*, *Juniperus procera* in the cool zone.

7.2.2 Sampling and analysis

Site selection

Site selection and sample collection was done between May and July 2010. The criteria used to select the study district includes: i) availability of different-aged exclosures and control sites adjacent or near to the respective exclosures, ii) availability of exclosures in different agro-ecological zones, and iii) comparable or similar exclosures management levels. Based on the selection criteria, discussions and consultation took place with the Agriculture and Rural Development Offices (ARDO) in North Wello zone to identify study districts. During the selection process, out of districts in the North Wello zone, the Kobo, Gubalafto and Habru districts were shortlisted. Further discussions and reconnaissance visits were made in the shortlisted districts to identify a representative site. Accordingly, Gubalafto district was selected for the study.

In the following, agro-ecological zones were delineated on a 1:50,000 scale topographic map. Then exclosures in different agro-ecological zones were identified and located on the map. The cool and mild zones cover a large area (72%) of the district and because most exclosures are located within these zones. Thus, these zones were determined for the sampling. Then, 18 exclosures aged between 8 and 27 years were identified. Because of budget and time reasons, out of the 18 exclosures, 10 exclosures were screened and revisited. Finally, among these, exclosures with similar age and comparable management level and topography were selected: the Lenche-Dima and Ayda-Tig exclosures in the mild zone and the Zendo-Girat and Abo-Dur exclosures in the cool zone (Figure 7.1). The Lenche-Dima and Zendo-Girat exclosures were 10 years old, while the Ayda-Tig and Abo-Dur exclosures were 27 years old. The exclosures have been closed since 1982 and 1999, respectively. Open areas adjacent to the exclosures that have been influenced by free livestock grazing and firewood collection were selected as a control.

In order to assess the possible impact of topography on the variability of the performance of exclosures with respect to soil fertility restoration, each sampling site was further divided in three landscape positions, i.e., upper, middle and lower (Figure 7.3). The landscape positions were determined based on site observations and contour lines on the topographic map. The upper landscape position of the exclosure receives little or no runoff, the middle landscape position is partly erosion zone that receives runoff from the upper slope and generates cumulated runoff to the lower landscape position. Finally, sampling points were plotted on topographic maps (1:50,000 scale), and coordinates of each point were calculated from the map to facilitate the transfer of the points on the ground.

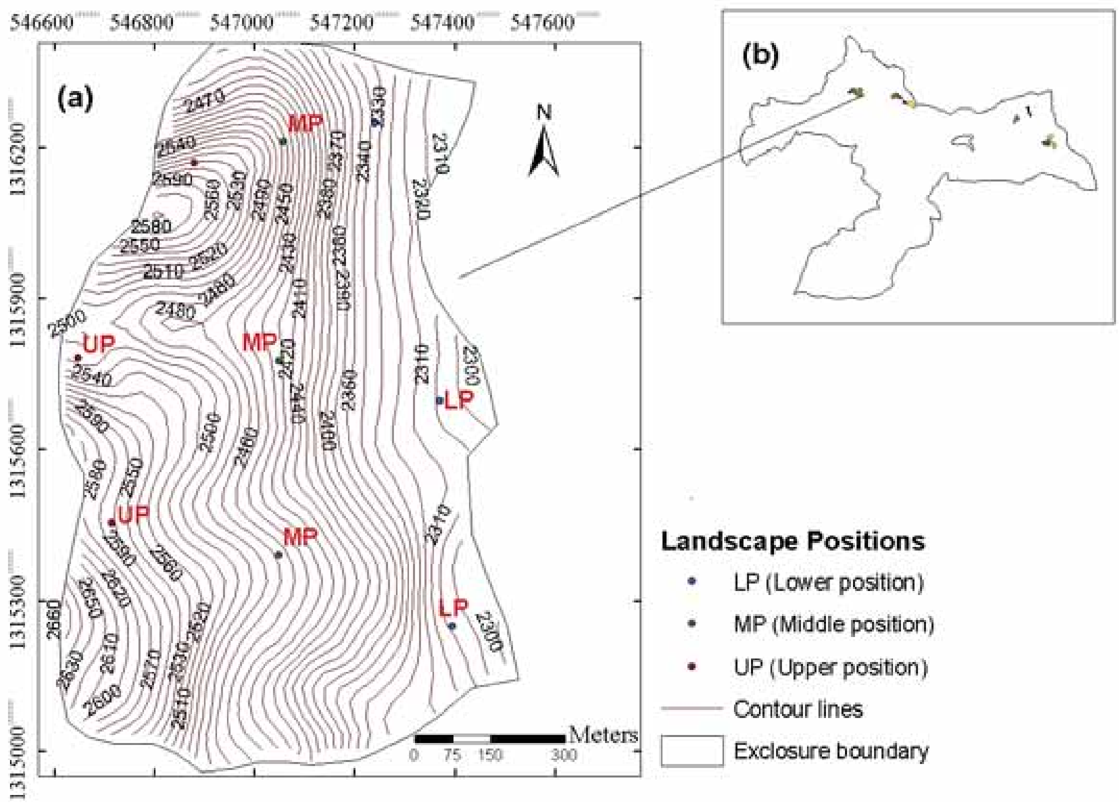
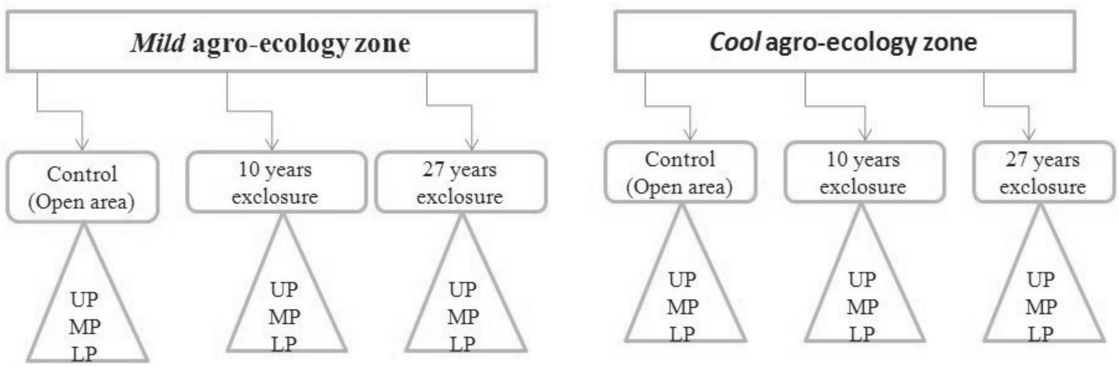


Figure 7.3 Abo-Dur exclosure sampling plots across the slope positions (a) and Abo-Dur exclosure within Gubalafto district (b)

Soil sampling and analysis

Following identification of sampling sites in the mild and cool agro-ecological zones, each site was further subdivided into three landscape positions. A 1:5,000 scale base map was prepared for each sampling site (exclosure). These maps were used to demarcate the three landscape positions. Three points (replicates) were randomly located on the base maps in each landscape position. The slopes of the randomly selected points were taken in consideration to make representative sampling in similar landscape position based on contour line depicted on topographic map. Subsequently, coordinates of the individual sampling points were calculated from the maps and stored in global positioning system (GPS) to help to locate each point on the ground.

During sampling, points plotted on the base maps were transferred to the ground with the help of GPS using the coordinate values stored in the GPS. Then, sampling plots measuring 5 m x 4 m were marked on the ground keeping the point transferred from the base map at the center of the plot. The sampling sits and plots were designed to assure maximum possible representativeness for the test (Figure 7.4). Soil samples were collected at 1 m intervals from four sides and from the diagonals of the plots in 15 cm depth using a hand auger. The samples from each auger points in a sampling plot were thoroughly mixed, composited and bagged. Accordingly, 9 samples were collected from each exclosure and the control (open area). A total of 54 composite soil samples were collected from the six sites, i.e., 27 samples from the mild and 27 samples from cool zones.



Note: Landscape positions: i.e., UP, MP and LP = upper, middle and lower positions, respectively

Figure 7.4 Schematic presentation of exclosure sampling

The soil samples were air dried, crushed and sieved (2 mm mesh). Soil texture, pH, electrical conductivity (EC), organic carbon (OC), available phosphorus (av. P), total nitrogen (TN), exchangeable bases, i.e., exchangeable calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}) and sodium (Na^{+}) and cation exchange capacity (CEC) were determined. Analysis was done using standard laboratory procedures. Accordingly, soil reaction and particle-size distribution were determined using glass electrode and hydrometer, respectively by Van Reeuwijk (2002) methods. Exchangeable bases and CEC were determined by the ammonium acetate method at pH 7 as described by Rowell (1994), OC was determined by the Walkley and Black (1934) method and TN by the Kjeldahl method as described in Black (1965). The Olsen et al. (1954) method was used to determine available P. The analysis was done at the National Soils Testing Laboratory in Addis Ababa, Ethiopia.

Vegetation cover survey

Tree transects on each site were laid out across the landscape based on the previous soil sampling scheme. Three nested quadrats were positioned along transects at lower, middle and upper landscape positions and used to estimate vegetation cover. At each vegetation estimation point, a 2 m by 2 m quadrat was nested at the center of the 10 m by 10 m quadrat. The main- and sub-quadrats were used to visually estimate canopy and ground cover, respectively. The vegetation cover estimation was done for all exclosure and control (open) sites in three landscape positions (lower, middle and upper slope) in three replicates, resulting in 54 main- and sub-quadrats each. Physical SWC structuers, vegetation types and the dominant tree species were recorded during transect walk.

Statistical analysis

The soil laboratory data were statistically analyzed by analysis of variance (ANOVA) in SPSS version 17. The differences in soil properties between the different ages, agro-ecological zones and landscape positions of the exclosures were analyzed using statistical analyses techniques with the aim of inferring the impact of the different factors on soil fertility restoration. A general linear model (univariate) was employed taking soil properties as dependent variables, and ages, agro-ecological zones and landscape positions as fixed factors. The test was first conducted using a nested model, which considers interaction of the factors. The nested model is given as:

$$y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \varepsilon_{ijk} \qquad (7.1)$$

where: y_{ijk} = dependent variables (soil physico-chemical properties); μ = sample mean; α_i = effect of agro-ecological zones; β_j = effect of age; γ_k = effect of landscape position; $(\alpha\beta)_{ij}$ = effect of interaction of agro-ecological zones and age; $(\alpha\gamma)_{ik}$ = effect of interaction of agro-ecological zones and landscape position; $(\beta\gamma)_{jk}$ = effect of interaction of age and landscape position; $(\alpha\beta\gamma)_{ijk}$ = effect of interactions of agro-ecological zones, age and landscape position, ε_{ijk} = random error.

The data were statistically analyzed by use of the above nested model. The interaction of fixed factors revealed insignificant differences throughout. The data were also examined for likelihood ratio test before rejection of the null hypothesis (nested model) using STATA (version 12). The test revealed lower probability values, which implies that the observed outcome was much less likely to occur under the null hypothesis than a simplified model, which disregards interactions of the fixed factors. Therefore, the above nested model (null hypothesis) was reduced to the following simple model:

$$y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + \varepsilon_{ijk} \tag{7.2}$$

Note: for the legend see the nested model.

Furthermore, to distinguish the relation of soil properties with each other, the soil analysis data were also checked for statistical correlation using a bivariate correlation analysis in SPSS version 17.

7.3 Results and discussion

7.3.1 Changes in biophysical features of exclosures

The vegetation cover, structure and composition of the exclosures showed clear differences in relation to age and agro-ecological zone, but there were no regular trends across the slope positions. Vegetation type and cover changed with increasing age of the exclosures (Table 7.1, Table 7.2, and Figure 7.5). As a result, the 10-year-old exclosures were largely dominated by grasses and bushes (Figure 7.5 a and c) where the average ground and canopy covers accounted for 60.5% and 19%, respectively. The 27-year-old exclosures were dominated by large trees (Figure 7.5 b and d), and had 67% ground and 69% canopy cover (Table 7.1). On the other hand, marginal lands left open for free grazing showed high biomass degradation (Figure 7.5 e and f), i.e., the canopy and ground cover were less than 5% and 25%, respectively (Table 7.1). Degraded land was first inhabited by opportunistic herbaceous vegetation and grasses, which were followed by relatively higher-layer vegetation (shrubs) succeeded by bushes and/or trees (Table 7.2). Similarly, gradual replacement of lower-layer by higher-layer vegetation with increasing age of the exclosures was reported in various studies (Khater et al. 2003; Descheemaeker et al. 2006; Oba et al. 2006). Vegetation structure and composition variation play an important role in soil fertility restoration.

Table 7.1 Vegetation cover of exclosures and control sites by age, agro-ecology and landscape position

Sampling site	Age	Agro-ecology	Ground cover (%)			Canopy cover (%)		
			LP	MP	UP	LP	MP	UP
Abo-Dur	27	Cool	75	63	67	80	87	80
Zendo-Girat	10	Cool	55	58	55	20	32	17
Open site	0	Cool	22	25	20	0	0	2
Ayda-Tig	27	Mild	68	77	52	63	53	50
Lenche-Dima	10	Mild	60	65	70	15	10	18
Open site	0	Mild	20	25	20	0	1	3

Table 7.2 Vegetation types and SWC structures in exclosures and control sites

Sampling site	Vegetation type	SWC structures
Abo-Dur	Trees, bushes, grass, shrubs, herbs	Hillside terraces, cut-off drains
Zendo-Girat	Grasses, shrubs/herbs, bushes, trees	Hillside terraces, micro-basins, check-dams, trenches
Open site	Grasses, bushes, shrubs and trees	Non
Ayda-Tig	Trees, bushes, grass, shrubs, herbs	Hillside terraces, cut-off drains
Lenche-Dima	Grasses, shrubs/herbs, bushes, trees	Hillside terraces, micro-basins, check-dams trenches
Open site	Bushes, shrubs, grasses and trees	Non

Note: *Vegetation types are listed in the order of abundance from higher to lower.*
Physical SWC structures in the older exclosures have been deteriorating due to regular sedimentation within successive structures

Climate, particularly rainfall and temperature, influences vegetation production, types and structure. Hence, the agro-ecological zone of an exclosure determines not only vegetation cover but also vegetation type (Table 7.2). The two agro-ecological zones in the study area have specific climatic features and are located in different altitude ranges. Exclosures vary due to the differences in climatic conditions and other environmental attributes (Descheemaeker et al. 2006; Aynekulu et al. 2009; Mekuria et al. 2011).

d) Ayda-Tig exclosure (mild, 27 years old)

b) Abo-Dur exclosure (cool, 27 years old)

c) Lenche-Dima exclosure (mild, 10 years old)

a) Zendo-Girat exclosure (cool, 10 years old)

e) Open area (mild)

f) Open area (cool)

Figure 7.5 Different-aged exclosures and control sites in cool and mild agro-ecological zones in Gubalafto district

The results of the present study reveal typical vegetation types in the two agro-ecological zones. For example, *Acacia asak*, *Carissa edulis*, *Cupressus lusitanica*, *Erica arborea*, *Eucalyptus globulus*, *Euphorbia abyssinica*, *Hagenia abyssinica*, and

Juniperus procera were typical species in the cool zone exclosure while *Acacia saligna*, *Acacia seyal*, *Aloe ferox*, *Eucalyptus camaldulensis,* and *Euclea schimperi* were typical in the mild zone. The tree types identified as typical for the cool and mild zones are similar to those in the classifications by Bekele-Tesemma et al. (1993). Other studies also reported that differences in climatic and environmental conditions were attributed to vegetation cover, and structure variation (Descheemaeker et al. 2006; Mekuria et al. 2011). The vegetation also showed differences in cover, where the cool zone tended to have a higher cover than the mild zone (Table 7.1). The difference in vegetation types in the two zones could play a significant role in determining the soil restoration rate.

The biophysical conditions of the exclosures did not show differences due to slope change. The study area is densely populated (Chapter 3). Consequently, people live and carry out agricultural activities near marginal lands. Particularly the lower boundaries of exclosures are close to settlement areas, grazing and cultivated lands, which could results in occasional disturbances. During the field survey, it was observed that exclosures had SWC structures such as hillside terraces, micro-basins, cut-off drains and trenches (Table 7.2, Figure 7.6). As per the district agriculture office and community information, the SWC structures were constructed before implementation of the exclosures. The purpose of SWC structures is *in-situ* soil and water conservation. From our observations, management level and the SWC constructions play a more important role regarding the vegetation cover in the exclosures than slope difference.

Figure 7.6 Physical SWC structures constructed before exclosure

7.3.2 Variation of soil fertility restoration across age of exclosures

This study revealed statistically significant differences in soil fertility status between degraded lands (open site) and 10- and 27-year-old exclosures. Among the different soil properties examined, TN and OC showed statistically significant increases with age of the exclosures while CEC showed only marginal differences. On the other hand, other soil properties did not show statistically significant differences (Table 7.3). Though some soil nutrients did not show statistically significant differences, available P, and exchangeable K^+ and Mg^{2+} showed a similar increasing trend to that of OC and TN.

Table 7.3 Average topsoil properties across age of exclosures

Age	pH (H_2O)	pH (KCl)	EC (ds/m)	TN (%)	OC (%)	av. P (ppm)
27-years	7.4	6.0	0.13	0.28^{da}	2.52^{db}	7.7
10-years	7.4	6.0	0.11	0.23^{b}	2.31^{c}	4.1
Control	7.5	6.1	0.14	0.16	1.64	3.9
F^{-value}	0.86^{ns}	0.94^{ns}	1.26^{ns}	9.73^{***}	5.36^{**}	1.82^{ns}

Age	Exchangeable bases and CEC (cmol(+)/kg)					Particles size distribution (%)		
	Na^+	K^+	Ca^{2+}	Mg^{2+}	CEC	Sand	Silt	Clay
27-years	0.31	0.96	22.43	4.90	36.3^{dd}	55	26	19
10-years	0.37	0.59	23.31	4.58	37.7^{b}	58	25	17
Control	0.31	0.66	22.61	4.72	35.0	52	29	19
F^{-value}	2.79^{ns}	2.18^{ns}	1.08^{ns}	1.09^{ns}	3.06^{*}	2.29^{ns}	1.80^{ns}	2.03^{ns}

Note: *The superscripted letters (a, b, c & d) of numbers in the columns indicate that the given soil property difference is significant (a) at P = 0.01, significant (b) at P = 0.05, significant (c) at P = 0.1 and (d) non-significant between mean values of subsequent exclosure age/agro-ecological zone/landscape position (Tukey HSD).*

For example, in the 4th column and 1st row TN = 0.28^{da} indicates that TN mean of 27-year-old exclosure is non-significantly different to that of the 10-year-old exclosure (d) but differences are significant at P = 0.01 with control (a).

F^{value} is *** significant at P = 0.01, ** significant at P = 0.05, * significant at P = 0.1, and ^{ns} non-significant

EC = electrical conductivity, TN = total nitrogen, OC = organic carbon, av. P = phosphorus (available), CEC = cation exchange capacity, Sample size by age (n) = 18 and overall sample size (N) = 54

Multiple comparisons (Tukey HSD post hoc tests) between the soils of the three age categories (control, 10- and 27-year-old exclosure) showed that the 27-year-old exclosures had statistically significantly higher TN ($P < 0.001$) and OC ($P = 0.009$) contents than soils of the open (control) sites. Likewise, soils of the 10-year-old exclosures also had statistically significantly higher TN ($P = 0.045$) and OC ($P = 0.059$)

contents than the control site where mean differences are significant (Table 7.3). On the other hand, there was no significant OC and TN difference between soils of the 10- and 27-year-old exclosures. Self-restoration of degraded land through exclosures has shown not only vegetation but also soil fertility restoration and carbon sequestration (Tefera et al. 2002; Asefa et al. 2003; Kalinina et al. 2009). The self-restoration processes enhance regular soil OM addition (Kalinina et al. 2009).

The differences in OC and TN content were likely due to the differences in OM input as the control sites might have minimal OM input due to continued biomass removal through livestock grazing, woody material collection and soil depletion through erosion (McIntosh et al. 1997; Descheemaeker et al. 2009; Fu et al. 2008). On the other hand, in the exclosures flora regeneration is enhanced, which in turn improves soil OM input (Mekuria et al. 2007; Kalinina et al. 2009; Mekuria et al. 2011). OC restoration rate in the first 10 years was 41% (6.7 g/kg) whereas in the subsequent 10 years it was only 9% (2.1 g/kg). In the early stages, the exclosures were dominated by rapidly recycling annual vegetation like grasses and herbs (Table 7.2). The vegetation dynamics of the current study agree with other reports (Fu et al. 2003; Khater et al. 2003; Asefa et al. 2003; Zhao et al. 2010). Results of a study conducted by Khater et al. (2003) on degraded land in Lebanon indicated that vegetation composition across the re-colonization processes follows the order of herbaceous (<0.5 m high), shrub and mixed trees (up to 7 m high). The grasses and herbs are gradually replaced by bushes and trees (Asefa et al. 2003; Khater et al. 2003). Grasses and herbs regularly add foliage, which quickly decomposes and is incorporated into the soil (Fu et al. 2008; Kalinina et al. 2009). Soil OM addition in degraded land that has a low initial OM level could bring about a remarkable change in a shorter period of time depending on the biophysical potential of the land under restoration. With time, exclosures are dominated by higher-layer vegetation such as bushes and/or trees (Khater et al. 2003) and consequently soil OM input is reduced (Fu et al. 2003; Kariuki et al. 2006; Mekuria et al. 2007).

The soils of the 10-year-old exclosures had a 44% (0.7 g/kg) higher TN content than those of the open sites. But in the 27-year-old exclosures a 22% (0.5 g/kg) higher TN content than in the soils of the 10-year-old exclosures was observed. This is in line with findings by Kariuki et al. (2006) where higher TN and OC restoration was observed in the first 50 years than in the following 100 years. In their study, the highest soil TN (280%) and OC (850%) restoration was observed between 20 and 55 years but then the rate decreased. The strong ($r^2 = 0.92$) correlation between soil OC and TN indicates that the factor determining the OC also affected the TN. Moreover, OC was positively and significantly correlated with most soil properties (Table 7.4). This confirms that OM addition is a base for soil fertility restoration. For example, soil OC was positively and significantly (P = 0.01) correlated (two tailed Pearson correlation) with TN, clay, CEC, and available P. The positive, significant (P = 0.01) and strong correlation ($r^2 = 0.92$) between OC and TN indicates that age of exclosure affects both in similar ways.

Table 7.4 Correlation of the major topsoil properties of the exclosures

	pH (H_2O)	Clay	Na	K	Ca	Mg	CEC	TN.	OC
Clay	0.048								
Na	0.013	0.044							
K	0.000	0.247	-0.024						
Ca	0.071	-0.026	0.167	-0.120					
Mg	0.182	0.098	0.152	0.022	0.516**				
CEC	0.083	-0.005	0.374**	0.057	0.511**	0.254			
TN	0.135	0.335*	0.134	0.245	0.126	0.291*	0.395**		
OC	0.147	0.421**	0.233	0.292*	0.137	0.276*	0.375**	0.921**	
Av.P	0.038	0.202	-0.143	0.441**	-0.146	0.169	0.092	0.422**	0.436**

Note: *** Significant at P = 0.01 level (2-tailed).*
** Significant at P = 0.05 levels (2-tailed)*
Values are Pearson Correlation coefficients (r), for n = 54

Generally, age of exclosures had no significant effect on pH, EC and exchangeable bases. Soil pH was only slightly different ($\Delta pH = 0.1$) between the soil of the exclosures and the open sites, for both pH measured in soil:water and soil:KCl suspensions, i.e., pH[H_2O] and pH[KCl], respectively. Age of the exclosure had insignificant effect on soil texture due to the fact that soil texture is an inherent property that depends on parent material and weathering rather than on OM addition. Reduction of soil erosion due to exclosure may not play a significant role in changing soil texture, as the soils are shallow and have a coarse texture. The average available P content of the open sites and 10- and 27-year-old exclosures was 3.9 ppm, 4.1 ppm and 4.7 ppm, respectively, but the differences were insignificant. Generally, the findings in this study are similar to those of other studies where soil fertility restoration due to exclosure was rapid at the earlier age and decreased with exclosure age (Richter et al. 1999; Fu et al. 2003; Kalinina et al. 2009).

7.3.3 Exclosure soil fertility restoration variation across agro-ecological zones

Climate is one of the soil-forming factors, as rainfall and temperature influence soil formation processes through influencing organic matter input and mineralization (Franzluuebbers et al. 2001; Zhao et al. 2010). Soils of the exclosures in the mild zone had a significantly higher pH than in the cool zone (Table 7.5).

Table 7.5 Average topsoil properties of exclosures across agro-ecology

Agro-ecology	pH (H_2O)	pH (KCl)	EC (ds/m)	TN (%)	OC (%)	av. P (ppm)
Mild	7.6	6.3	0.15	0.27	2.70	7.2
Cool	7.3	5.8	0.10	0.17	1.62	3.2
$F^{\text{-value}}$	5.52^{**}	21.92^{***}	20.36^{***}	20.66^{***}	22.08^{***}	4.81^{**}

Agro-ecology	Exchangeable bases and CEC (cmol(+)/kg)					Particles size distribution (%)		
	Na^+	K^+	Ca^{2+}	Mg^{2+}	CEC	Sand	Silt	Clay
Mild	0.37	0.80	23.03	4.84	37.8	49	30	21
Cool	0.28	0.68	22.54	4.63	34.8	61	23	16
$F^{\text{-value}}$	11.44^{**}	0.63^{ns}	0.88^{ns}	1.35^{ns}	11.55^{*}	26.9^{***}	23.3^{***}	14.3^{***}

Note: *Sample size by agro-ecological zone (n) = 27 and overall sample size (N) = 54, other abbreviations are similar to table 7.3*

The EC of the soil was also significantly different where a lower EC was measured in the soils of exclosures in the cool (mean EC of 0.10 ds/m) than in the mild zone (mean EC of 0.15 ds/m). Temperature and precipitation directly influence pedogenic processes thereby influencing pH and EC (Franzluuebbers et al. 2001). Hence, the differences in soil pH and EC in the mild and cool zones could be attributed to the differences in pedogenic processes as result of climate differences rather than to the impact of exclosure.

Soils of the exclosures in the two agro-ecological zones also showed significant differences in TN ($P < 0.001$) and OC ($P < 0.001$). The soils in the mild zone had a significantly higher TN and OC content than those in the cool zone. Results also indicate that the soils of the mild exclosures had 64% (8.7 g/kg) higher OC and 61% (1.2 g/kg) higher TN content than those in the cool zone (Table 7.6). A comparison based on age and agro-ecological zone shows that soils of the mild exclosures had a higher average OC content than soils in the corresponding age exclosures at cool zone except for some deviation in the 10-year-old exclosure (Figure 7.7). However, the average TN was higher than in the corresponding age exclosure in the cool zone.

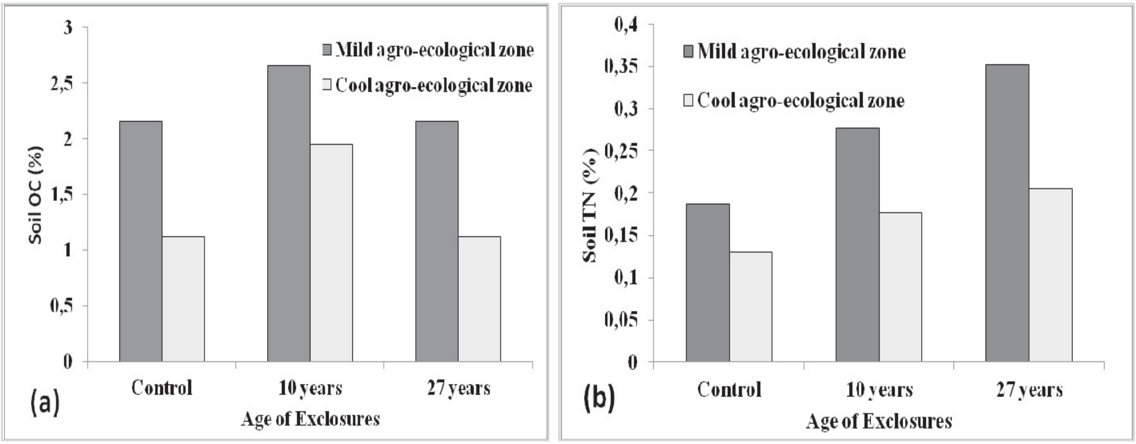


Figure 7.7 Soil OC (a) and TN (b) contents of exclosures across age and agro-ecological zones

Table 7.6 Soil OC and TN content in exclosures across age and agro-ecological zones

		Mean TN content (%) Agro-ecology		Mean OC content (%) Agro-ecology	
No	Exclosure age	Mild	Cool	Mild	Cool
A	Control	0.19	0.13	2.16	1.12
B	10 years	0.28	0.18	2.66	1.95
C	27 years	0.35	0.21	2.16	1.12
	Average of B and C (%)	0.31	0.19	2.41	1.53
	Average of B and C (g/kg)	3.15	1.92	24.10	15.35

The soils of the exclosures in the mild zone also had statistically significantly higher available P than those in the cool zone. The major sources of P are mineral elements. However, the C/P ratio, which reflects organic P release through OM mineralization, did not differ. This could imply that the available P differences were unlikely due to the OM input differences. The lower available P in the cool zone could be due to higher P fixation. The differences in available P between the two zones could be due to differences in the pedogenic process and not to the influence of climate on OM.

Exchangeable bases except Na^+ were not significantly different between agro-ecological zones. In contrast to the exchangeable bases, the CEC significantly (P = 0.002) varied between agro-ecological zones. Like OC, TN and most other soil properties, a higher CEC was measured in the soils in the mild (37.8 cmol (+)/kg) than in the cool zone (34.8 cmol (+)/kg). The CEC of soil is determined by the two colloidal particles clay and humus (Oorts et al. 2003). The CEC correlated positively and significantly (P = 0.01) but not so strongly (r^2 = 0.375) with OC. This indicates dependency of the CEC on OM. The agro-ecological zone showed statistically significant soil texture differences. Soils in the mild zone exclosures had 5% higher clay and 7% higher silt than the soils in the cool zone.

7.3.4 Exclosures soil fertility restoration variation across landscape

The results of the present study reveal that landscape position of the exclosure did not show significant differences in most soil properties such as EC, TN, OC, exchangeable bases (Na^+, K^+, Ca^{2+} and Mg^{2+}), CEC and texture (Table 7.7). Only available P showed statistically significant differences across landscape position of the exclosures. It significantly increased (P = 0.05) towards the upper landscape positions in contrast to the direction of the soil erosion and deposition process. On average, available P was 3.4 ppm at the lower, 3.8 ppm at the middle and 8.5 ppm at the upper landscape positions of the exclosures.

Table 7.7 Average topsoil properties across landscape position of exclosures

landscape position	pH (H_2O)	pH (KCl)	EC (ds/m)	TN (%)	OC (%)	av. P (ppm)
LP	7.4	6.0	0.12	0.19	1.94	3.4^{dc}
MP	7.5	6.1	0.12	0.25	2.39	3.8^{c}
UP	7.4	6.0	0.13	0.23	2.14	8.5
F^{-value}	0.77^{ns}	0.57^{ns}	0.29^{ns}	1.94^{ns}	1.30^{ns}	3.26^{**}

landscape position	Exchangeable bases and CEC (cmol(+)/kg)					Particles size distribution (%)		
	Na^+	K^+	Ca^{2+}	Mg^{2+}	CEC	Sand	Silt	Clay
LP	0.32	0.63	22.92	4.71	35.92	55	27	18
MP	0.33	0.62	23.15	4.86	36.19	55	27	18
UP	0.34	0.97	22.28	4.63	36.84	55	26	19
F^{-value}	0.37^{ns}	2.23^{ns}	1.01^{ns}	0.59^{ns}	0.38^{ns}	0.04^{ns}	0.07^{ns}	0.02^{ns}

Note: *Landscape position, i.e., LP = lower position, MP = middle position, and UP = upper position Sample size by landscape position (n) = 18 and total sample size (N) = 54, other abbreviations are same as table 7.3*

SWC structures constructed during/before exclosure implementation have played vital role to intercept of runoff and enhanced infiltration. The SWC structures enhance *in-situ* soil conservation and minimize material redistribution through erosion from the upper towards the lower landscape positions. Thus, structures retain existing or newly dropped litter *in-situ* than transported down-slope. It could be possible to conclude that the structures played complementary conservation effect to that of exclosure restoration. Therefore, the non-significant soil properties differences across landscape position could be attributed to the complementary effect of the physical SWC structures.

Converse to other research, this study indicates that soil nutrients are fairly uniformly distributed across the landscape positions of the exclosures. The lower landscape positions are mostly in close vicinity to settlements and cultivated and grazing lands. Consequently, these parts of the exclosures are prone to occasional human and livestock disturbances. The interferences remove organic matter through cutting and livestock grazing, which in turn negatively influenced soil fertility restoration. As a result, most soil nutrients except exchangeable bases were low at lower landscape positions (Table 7.7). These soils on average had 4.5 g/kg less OC, 0.6 g/kg less TN and 11% less available P than soils in the middle landscape positions. Similarly, soils in the lower landscape positions on average had 2 g/kg less OC, 0.4 g/kg less TN, 150% less available P and 0.13 g/kg less exchangeable K^+ than the soils in the upper landscape positions.

7.4 Summary and conclusions

Among the different SWC interventions, exclosure is a widely implemented activity for rehabilitating degraded lands. Despite the massive SWC interventions, their impact has not been sufficiently studied. Thus, this study focused on analyzing the impact of exclosure to restore soil fertility and evaluated the restoration variation across age, agro-ecological zone and landscape position of the exclosures. The study was conducted in Gubalafto district of the North Wello zone in Amhara National Regional State of Ethiopia. Soil data were collected from exclosures (10- and 27-year-old) and control (open) sites in the mild and cool agro-ecological zones. The exclosures and the controls sites were further subdivided in upper, middle and lower landscape positions.

Composite soil samples to 15 cm depth were collected from sampling plots (20 m^2 each) for each age, agro-ecological zone and landscape position in three replicates. The samples were analyzed for texture, pH, OC, av. P, TN, exchangeable bases and CEC using standard laboratory methods. The soil laboratory analysis results were statistically analyzed by analysis of variance (ANOVA) using the general linear model (univariate), in SPSS 17.

Among the different soil properties analyzed and statistically tested, only OC and TN contents showed statistically significant differences with exclosure age, but the differences were nonlinear. Soils of the exclosures had significantly higher OC and TN contents than the open sites but no significant difference was observed between the 10- and 27-year-old exclosures. Accordingly, soils of the 10-year-old exclosures had statistically significantly higher OC and TN contents than those of the open sites. Similarly, soils of the 27-year-old exclosures had significantly higher OC and TN contents than those of the open sites. The differences between soil OC and TN content of the control sites and 10-year-old exclosures were 41% (6.7 g/kg) and 44% (0.7 g/kg), respectively, while differences in OC and TN between soils of 10- and 27-year-old exclosures were only 9% (2.1 g/kg) and 22% (0.5 g/kg), respectively. This implies that soil OC and TN restoration rate of the exclosures increased at a decreasing rate after some time and reached a steady state with time. Retardation of the soil OC and TN restoration rate with exclosure age could be attributed to change in biomass quantity and quality, which in turn determine OM input and mineralization. Soils of the 27-year-old exclosures had a lower C/N ratio than soils of the 10-year-old exclosures and the control sites OC and TN were highly interdependent as manifested through their positive, strong (r^2 = 0.92) and significant (P = 0.01) correlation.

Comparison of soil properties across agro-ecological zones of the exclosures revealed statistically significant variation. The soils of exclosures in the mild zone had statistically significantly higher pH, EC, OC, TN and available P, silt and clay contents than those in the cool zone. Although exchangeable bases (Ca^{2+}, Mg^{2+} and K^{+}) contents showed non-significant differences between the two agro-ecological zones, higher mean values were observed in the mild zone. The higher soil nutrient contents of exclosures in the mild zone can be attributed to the effect of agro-ecological zone/climate on biomass production, vegetation type, (Lawrence and Bruce 2005) and OM mineralization (Zhao et al. 2010)

As opposed to various studies (e.g., Fu et al. 2003; Moges and Holden 2008; Sariyildiz et al. 2008), most soil properties did not show significant differences with landscape positions of exclosures. The close vicinity of the lower landscape position of the exclosures to settlement, grazing and cultivated lands make this part prone to recurrent livestock and human interference. The physical SWC structures in the exclosures enhanced *in-situ* soil and water conservation and thereby reduced fertility restoration variation across landscape.

From the above analysis the following can be concluded:

i. OC and TN restoration rate significantly increased with exclosure age and the restoration rate reduced with time, indicating steady state. Steady state OC and TN differences could be due to change in biomass quantity and quality with exclosure age. Biomass quality and quantity in turn determine OM input and mineralization.

ii. Soil fertility significantly varied with agro-ecological zone of the exclosures, where higher soil fertility was observed in the mild than in the cool zone. This could be due to the effect of agro-ecological zone (climate) on vegetation types and OM mineralization.

iii. Soil fertility restoration showed insignificant differences with landscape position of the exclosures, which is attributed to conservation complementary effect of physical SWC structures.

8 IMPLICATIONS OF SOIL AND WATER CONSERVATION MEASURES FOR LAND REHABILITATION- A SYNTHESIS

8.1 Introduction

In an effort to reduce degradation and restore the degraded lands, soil and water conservation (SWC) measures have played a considerable role in Ethiopia (Gebremichael et al. 2005; Vancampenhout et al. 2006; Nyssen et al. 2007). The empirical analyses presented in the previous chapters provide tangible evidence of the positive impacts of SWC, particularly exclosure and farmland terracing, on soil fertility maintenance and the associated benefits. This chapter presents a synthesis of the implications of SWC measures for land degradation with particular emphasis on exclosure and terracing as analyzed in Chapters 4 to 7.

8.2 Conceptual framework of human-induced land degradation

Land degradation reduces the potential of land in providing sustainable ecosystem services. Land degradation gradually takes place over time. However, the manifestation time depends on the land´s resilience to degrading conditions and the intensity of the degrading factors. Factors are also mostly interwoven, and the deleterious effect of one could initiate the other processes. In the present study, cause and effect of land degradation is demonstrated using a conceptual framework (Figure 8.1).

Nearly 40% of the study area has slopes over 30% of which 10% are slopes of more than 60% (Chapter 4). Land potential for agricultural use has been limited not only by slope but also by shallow soil depths and rock outcroppings. Moreover, the study area is characterized by high population density and rapid growth rate. The population of the country increased 6-fold from 12 million at the beginning of the 1900 to 74 million in 2007 (Logan 1946; Sørensen and Bekele 2009). Similarly, in the study area, population density and growth rate was also very high. For example, the South Wello population grew by 3.4% between 1970 and 1994 (Tekle 1999). With the population increase, disturbance of natural resources such as forest and other vegetation due to free livestock grazing, expansion of settlement and cultivation increased (Tekle 1999). Forest degradation also increased due to uncontrolled cutting to satisfy the demand for household energy and construction and for income generating purposes (Pohjonen and Pukkala 1990; Feoli et al. 2002). The human and livestock intrusion on fragile lands has resulted in soil degradation and nutrient depletion and downstream sedimentation (Badege 2001; Feoli et al. 2002; Amsalu et al. 2007). Runoff water from degraded lands generates floods that encroach on productive plains and bottomlands, and ultimately shorten the life of reservoirs due to sedimentation. The Borchenna irrigation dam is a typical example in the study area, which was abandoned due to siltation within less than 10 years. The irrigation diversion of the River Alwha has led to riverbank erosion due to flash floods during heavy rain periods that reduce the irrigation command area. As a result, the land degradation processes in one or other way have affected agricultural production and productivity.

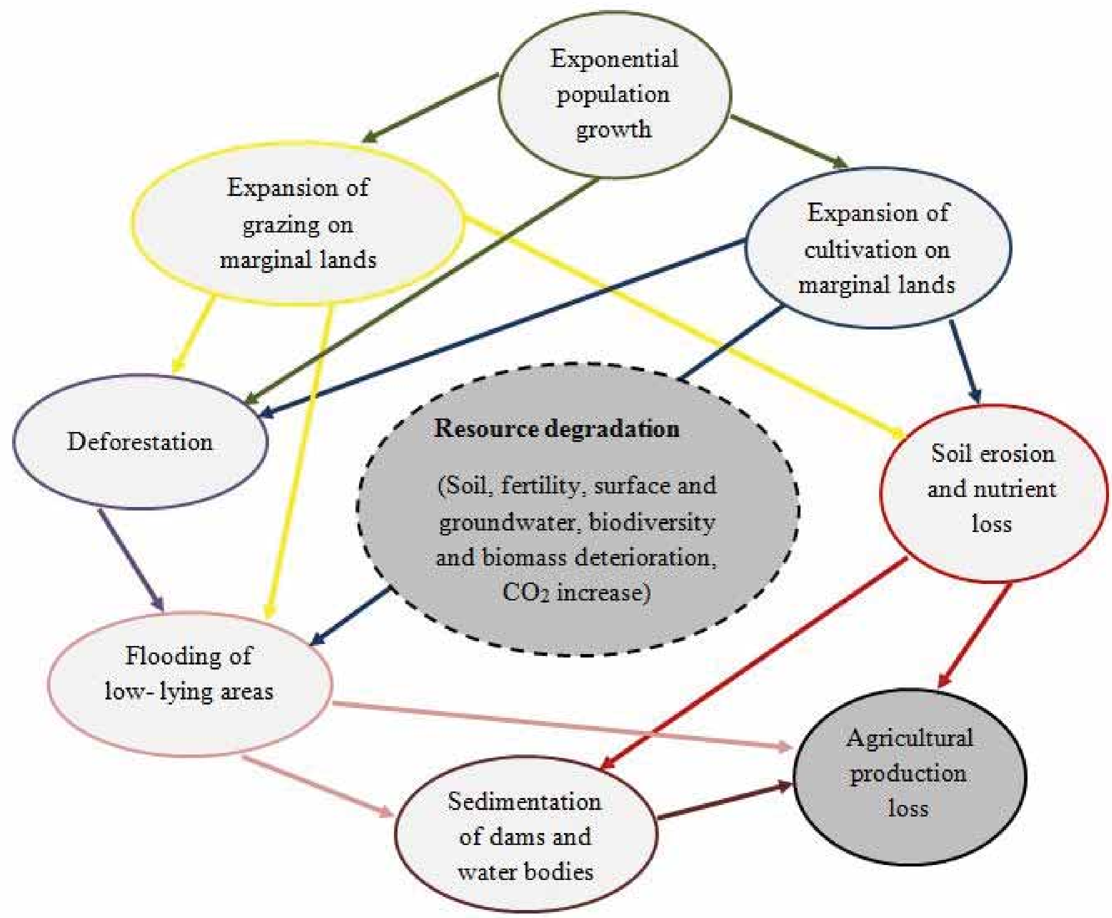


Figure 8.1 Conceptual framework of land degradation

8.3 Role of soil and water conservation for degraded land restoration

Studies have indicated that biological and mechanical SWC measures can help to reduce soil loss and regenerate vegetation (Carla et al. 2003; Fu et al. 2003; Mekuria et al.

2007; Kalinina et al. 2009). In the present study, the SWC measures reduced both the *in-situ* and *offsite* impacts of degradation. Mechanical structures such as terraces, check dams, tranches and micro-basins modify terrain through changing slope length and angel, which in turn reduces runoff velocity, enhances water infiltration and traps sediments washed down the terrain (Vancampenhout et al. 2006; Nyssen et al. 2007). Sediment accumulated behind the terrace provides suitable conditions for plants/crops through conserving nutrients and water (Dercon et al. 2003; Gebremichael et al. 2005; Vancampenhout et al. 2006).

Biological SWC measures such as exclosure, homestead tree plantation, reforestation and enrichment tree plantation within exclosures help to restore vegetation cover and diversity (Asefa et al. 2003; Carla et al. 2003; Fu et al. 2003). With vegetation cover restoration, beside soil fertility improvement through regular organic matter addition, the soil surface can also be protected from raindrop splash and scoring effects of runoff water. This reduces soil particle detachment and transportation. The vegetation intercepts the rainwater, which enhances infiltration and reduces runoff. The infiltrated water percolates into the ground (aquifer), which in turn improves the hydrology. People down-slope witnessed that spring discharges considerably increased after the exclosure, and even in some cases dried springs recovered. Flood risks and sedimentation on fertile farmlands by stones and gravely material has been reduced. These lands are mainly situated along streams. Thus, the *in-situ* and *offsite* impacts of SWC interventions ultimately led to sustainable agricultural production and productivity (Chapter 6).

In some areas, exclosures are divided among people who manage their land parcel and use grass through this system. The Kobo-Girana Valley Development Program (KFVDP) initiative can be cited as an example. They formed user groups and facilitated exclosure sharing among users, providing training on appropriate output use and management. As a result, the protected steep lands located above the farmlands showed reduced runoff, which had been damaging the cultivated lands. Following the exclosure practice, improved and traditional irrigation has also been expanded. Agriculture offices and NGOs have helped farmers to improve the traditional irrigation. Therefore, the SWC practices played a considerable role in improving the irrigation water supply through better recharge. Streams and springs, which were dried out or critically reduced during dry periods, considerably increased the base flow. Strong flash flooding from degraded lands was also reduced due to the mechanical structures and vegetation recovery. The structures intercepted runoff, and eroded soils and soil fertility in the exclosures also improved significantly (Chapter 7). Soil nutrient loss after farmland terracing was also considerably reduced (Chapter 5). As a result, crop yield on terraced farmland showed relatively stable conditions (Chapter 6). The effect of SWC on the restoration and rehabilitation of degraded lands is demonstrated by the conceptual framework given below (Figure 8.2).

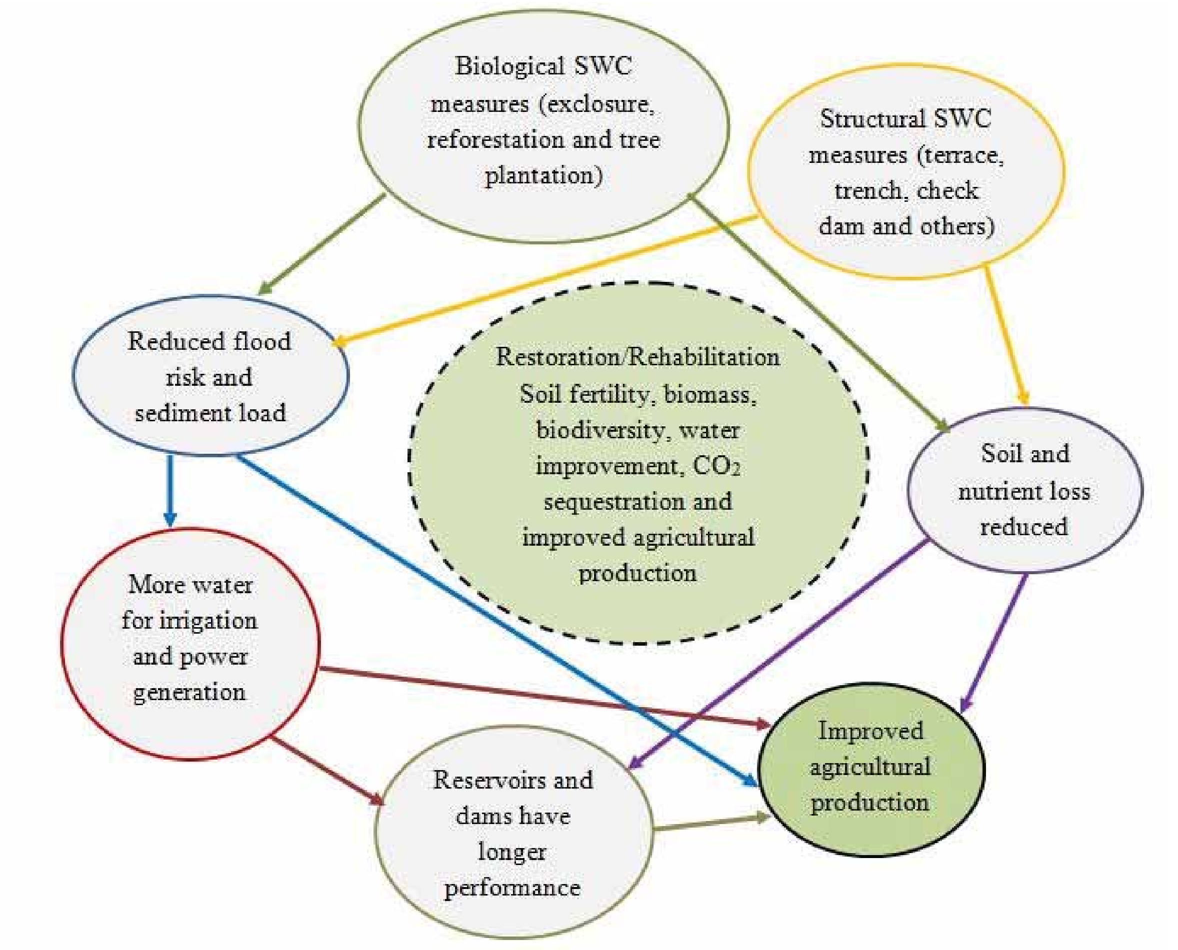


Figure 8.2 Conceptual framework demonstrating role of SWC measures in degraded land restoration

8.4 Short- and long-term implications of exclosures

Natural resource conservation planning failures could threaten sustainability and lead to complete rejection of the measures by the local community. Therefore, conservation interventions should critically consider the short- and long-term benefits and their implications. The benefits and shortcomings should be identified so that appropriate corrective measures can be taken at an appropriate stage. The current analysis shows that exclosures resulted in significant vegetation and soil fertility restoration (Chapter 7). Soils of the exclosures showed remarkable improvements in physico-chemical properties, particularly significant in the case of OC and TN restoration. The soil fertility restoration was mainly due to the impact of exclosures, which led to improve OM addition and mineralization. However, restoration showed spatial and temporal variability. Although soil fertility restoration varies with age, the rate tends to decrease with exclosure age, and this is in line with other studies (Asefa et al. 2003; Carla et al. 2003; Fu et al. 2003).

Self-restoration of degraded land through exclosure also showed species and cover dynamics; where the changes were from the lower to higher vegetation layer and order (Mekuria et al. 2011). SWC structures implemented at the beginning of exclosures also enhanced *in-situ* conservation. Consequently, as opposed to the common phenomena, a non-significant soil fertility gradient was observed across the terrain (Chapter 7). Moreover, exclosures had a positive impact downstream such as reducing flood hazards at lower terrain positions, decreasing farmland encroachment by gully and riverbank erosion, and improving the overall hydrology (Chapter 4).

The highlands in general and the study area in particular are densely populated and have a high livestock density, i.e., the study area with an average 76 TLU´s km^{-2} livestock and 134 persons km^{-2}. The area is also characterized by rugged topography, where steeper slope areas account for 40%. Moreover, about 90% of the population lives in rural areas where the economy entirely depends on agriculture (Chapter 3). These factors indicate competition for resources, thus the area needs careful land-use planning and management. The LULC changes, particularly conversion of marginal lands, originally covered by natural vegetation, to grazing and cultivation were due to population pressure (Chapter 4). The LULC analysis also revealed that less sloping lands with deeper soils are used for cultivation and settlements. Lands with slopes <30% are used for pasture only if there are drainage problems (Chapter 4). As in the other parts of the highlands, the livestock largely depend on crop residues. This indicates that the area has livestock feed problems, which calls for alternative forage production.

At an early stage, exclosures are mainly covered by grasses that are used as livestock feed. However, the grasses are gradually replaced by unpalatable species and higher layer vegetation (Angassa and Oba 2008; Zhao et al. 2010). This leads to an increased livestock feed problem. Studies conducted in the Borana area (southern Ethiopia) showed that exclosure and banning of traditional rangeland fires resulted in bush encroachment that radically altered the pasture quality and productivity. Therefore, failure of developing alternatives that optimize current and future demands could lead to further degradation (Oba et al. 2000; Angassa and Oba 2008).

Gradual replacement of palatable species and shortage of livestock feed could lead to further dependency on crop residues and an increased pressure on the limited pastures lands and open areas. This could result in severe degradation in these areas. Therefore, we recommend that exclosures should be planned and implemented in a way that considers resources conservation as well as sustainable long- and short-term benefits to the community. Exclosure use and management should be planned with defined purposes such as soil conservation (reduced soil erosion), flood and landslide control, forage production, biodiversity conservation, apiculture and other multipurpose. Planning also needs to include detailed management on how and when each activity should take place rather than taking corrective action. During the field study, it was observed that most exclosures have neither management nor utilization plans. This calls for strategic correction. Otherwise there will be a reduction in animal feed supply from exclosures, as they will become dominated by higher layer vegetation. There will also be further degradation of open areas and arable lands due to overgrazing and crop residue use as livestock feed would continue.

8.5 Implications of farmland terracing for soil fertility and crop yield

This study revealed that topsoil fertility gradients within a terrace did not exist, which is associated with the development of bench terraces. Sediment deposition and/or erosion gradients within a terrace are mostly minimized. Thus, the topsoil receives uniform runoff that adds/removes equal volumes of sediment within a terrace, as the slope variation low- and up-terrace is greatly reduced. Topsoil fertility restoration also showed insignificant differences across the terrain (Chapter 5). This indicates that terracing reduced soil erosion from upper to down-slope positions. The lack of topsoil fertility variation across the terrain also indicates that terracing reduced erosion and deposition processes. As soil erosion before terracing was severe (Hurni 1993), topsoil fertility stability in the presence of continued soil nutrient export through crop harvest and minimal fertilizer (organic and inorganic) use indicates that terracing played an appreciable role at least in maintaining the topsoil fertility status. Therefore, terracing reduced soil erosion and nutrient loss due to erosion.

The results of the crop yield analysis agreed with those on the impact on soil fertility through terracing. Crop yield showed only very slight changes with time, which indicates that terracing, helped to maintain production (Chapter 6). Crop yield (biomass and grain) also showed only slight changes across the terrain. The slight yield reduction from the lower to upper slope of the terrain could be a result of erosion before the terracing (Chapter 6). This indicates that terracing contributed positively to crop production stability. However, terracing negatively affected the productivity of crops sensitive to water logging such as wheat, and this led to yield gradients within the terraces. Yields of almost all crops showed significant differences within a terrace, where higher values were observed above the terrace riser. The yield gradient within a terrace could be attributed to soil depth, which resulted in differences in the soil water and nutrient storage capacity.

Grasses grown on terraces stabilize the structures and are also used as additional sources of livestock feed as long as the cut-and-carry system is used. Therefore, terracing maintained agricultural productivity and reduced erosion-induced land degradation. However, in order to improve productivity, nutrient depletion due to crop harvesting and other losses should be compensated through input use.

8.6 Implications of SWC-driven LULC change for resource restoration

Widespread efforts have been made to implement SWC measures in the past three decades with the aim of reversing land degradation. The measures, particularly exclosures, helped to restore the vegetation cover of marginal lands, especially on mountains and hillsides. Currently, the Wello area is largely covered by exclosures (Chapter 4). The MODIS data analysis revealed that the area covered by grassland/woody-grassland increased by 14.6%, which is due to the recent large-scale expansion of exclosures (Chapter 4). It was also observed that density and coverage of forests increased in the areas where the interventions were started earlier. In contrast, the area covered by degraded-woody vegetation decreased by 13%. This shows that degraded lands are improving as a result of the exclosures (Chapter 4). The LULC change from converted marginal lands to cultivation and grazing was driven by population pressure and lack of awareness. Although the population of the area continues to increase, the vegetation cover on the marginal land is improving. The change can be mainly associated with policy interventions that initiated enclosure of degraded lands by local actors, and people also have become aware of the benefits of the practice. They have witnessed that, after exclosure, productivity of the land improved and the land could be used as a source of hay. Moreover, flood hazards and farmland encroachment due to aggressive gullies and slumping river banks, and deposition of stony and gravely sediment from the hillsides on productive farmlands has been considerably reduced (Chapter 4).

Government policy has also played a significant role in initiating and enforcing the SWC interventions, e.g., the 1980 wild life and forest conservation and the 2005 rural land administration and use declarations. Active involvement of the government and NGO´s in SWC intervention, capacity building, research and incentives stimulated participation and raised people´s awareness level. The recent government policy partly solved the land ownership problem, where farmers are entitled to use the land, transfer it to family members and rent it for a fixed time period (Anonymous 2005; 2006). The policy also enforces proper land use. People living in areas where exclosures were established earlier recognized the positive impact of the intervention. In this regard, the NGO´s involvement also enhanced the adoption through incentives, e.g., payment in the form of food-for-work, farm tool provision, and capacity building such as workshops, short-term training and experience-sharing visits (Tekle 1999). Consequently, it is possible to conclude that the various policies in place so far and active involvement of the government and NGO´s in SWC play an important role in LULC change.

8.7 NDVI spatio-temporal variation as indicator of degradation/restoration

In this study, NDVI data are used to fill the analysis gap in the LULC assessment. The NDVI data analysis helped to identify degradation hotspots, which were not addressed by the LULC analysis. Moreover, the NDVI analysis helped to verify the area showing vegetation improvement. NDVI provides the opportunity to perform empirical manipulations through modeling in a given spatio-temporal resolution. The analysis considered all data sets that evaluated every pixel across time. The results indicate that the study area broadly experiences vegetation improvement, degradation or no change, which was not very clear in the LULC analysis (Chapter 4). The northeast, west and central northwest parts were identified as areas of vegetation degradation, whereas the central, east and southeast parts showed restoration or very slight change.

The restoration and degradation correlated neither with population density nor with topography. For example, Bugna, Kelela and Sayint districts are among the less populated areas, nevertheless they showed high vegetation degradation. On the other hand, although the population density of Guba-Lafto, Legambo and Tehuledere districts were higher, they showed considerable vegetation restoration. The latter districts have better accessibility than the former. Ambasel, Legambo and Gidan districts have highly rugged topography nonetheless, they also showed better restoration. The areas showing restoration are closer to all-weather roads and are adjacent to each other. Thus, access could contribute either to extension of the intervention, or actors used the advantage of accessibility to work in the area. The geographical continuity of rehabilitated areas could also indicate the significance of extension diffusion. The remotest areas showed vegetation degradation. Vlek et al., (2008) also reported higher degradation in areas under less population pressure and surmised that this was due to encroachment on marginal lands with limited carrying capacity. Therefore, location helped government policy implementation and extension work regardless of population density and geographic conditions. It can be concluded that development-actor commitment is crucial in replicating the conservation outcome of the accessible areas. Generally, the NDVI analysis provided better facilities to represent spatio-temporal vegetation dynamics and degradation/restoration patterns than the LULC analysis.

8.8 Overall implications of SWC for land restoration and livelihoods

Land degradation is a result of the interactive effects of resource misuse and climate change. The anthropogenic effect can be reduced through minimizing the drivers (Asefa et al. 2003; Khater et al. 2003; Nyssen et al. 2009). The recurring droughts the country has faced have exacerbated the problem (Tilahun 2006). Drought deteriorates the land production potential, which results in resources over-utilization in order to fulfill the people´s basic needs (Oba et al. 2000; Angassa and Oba 2008).

The conservation measures reduced soil and nutrient loss by water erosion. Even though considerable soil fertility gradients appeared in the earlier stage of terracing, the gradient reduced with the development of bench terraces (Sonneveld and Keyzer 2003; Dercon et al. 2003; Vancampenhout et al. 2006; Nyssen et al. 2007). Consequently, crop yield loss resulting from severe soil erosion was reduced (Chapter 6). The stable crop yield overtime indicates that terracing at least helped to maintain yields. The portion of the land used for terrace construction was not completely wasted, as this land is used for livestock feed production. In the crop-livestock system, the supplementary forage produced along the conservation structures can be regarded as a positive attribute.

Before the conservation intervention, stream banks and gullies were encroaching on productive farmlands, but encroachment was remarkably reduced after the conservation measures (Chapter 4 and 5). The rehabilitated stream banks and gully sides are used for forage and wood production. The field observations and discussions with farmers also clearly showed that the structural and biological conservation measures reduced both *in-site* and *offsite* damage resulting from soil erosion and runoff (Chapter 4). Generally, SWC interventions played an important role in the reduction of erosion-induced land degradation and agricultural production loss.

On the other hand, both the physical and biological SWC measures compete with land use. In the study area, farmers are facing livestock feed shortage in older exclosures, as the grass cover is replaced by higher layer vegetation. Farmers complained that they are facing feed shortages even for stall feeding, and complete exclusion of leaf-browsing animals like goats and camels forced them to destock these animals. Similarly, this and other similar studies showed considerable land reduction due to terracing. For example, in this study it was found that on average terraces occupy

6% of cultivable land, while Herweg and Ludi (1999) reported that terraces occupy 10 to 15% of the land.

The population growth rate is double that of agricultural production, which indicates the necessity of solutions in order to optimize the demand and supply. It is obvious that land has to be managed properly, otherwise sustainable production will be threatened. This calls for careful planning, since the livelihoods largely depend on agriculture. In this regard, the possible options could be implementation of supplementary livelihood options, especially for the young people who do not have farmland. Moreover, implementation of strategic land-use planning is equally important. It should consider allocation of parts of the exclosure for forage development and other uses. Physical SWC structures like bunds, terraces and check dams can also be used to produce forage grasses and trees. Terraces in the Maybar watershed are a good example, where grasses grown on the terraces are used as hay sources. Rehabilitated gullies and stream banks could also be used for forage production through the cut-and-carry system. Generally, SWC in general has positive impacts on agricultural production, nevertheless implementation of alternative livelihood options is most important in order to lessen the potential pressure on the land.

9 OVERALL SUMMARY AND CONCLUSIONS

9.1 General summary

The economy of Ethiopia largely depends on agriculture. However, the sector has been constrained by land degradation. In response to the land degradation, the government has been taking policy actions and implementing soil and water conservation measures (SWC) since the 1980´s. The conservation practices include both mechanical and biological measures on farmlands and degraded marginal communal lands. The main structures on farmland are terracing, while degraded marginal communal lands have been protected from human and animal interferences through exclosure and the terrain modified by constructing mechanical structures. In order to understand the impact of the SWC measures, particularly exclosure and farmland terracing, a study was conducted in North and South Wello zones of the Amhara National Regional State, Ethiopia. The study area is located between 10°12′ and 12°22′ north latitude and 38°30′ and 40°14′ east longitude. The study evaluated exclosure in soil fertility and vegetation restoration using soil samples and satellite data. The satellite data were used to analyze land-use/land-cover (LULC) and normalized differenced vegetation index (NDVI) change as an indicator of vegetation degradation and/or restoration. The study also evaluated the impact of farmland terracing on soil fertility and crop yield, and their spatio-temporal variability. Finally, a synthesis of the analysis results was conducted with respect to land restoration. The results of the analysis show a positive impact of the measures (exclosure and farmland terracing) in maintaining and/or restoring soil fertility, crop yield and vegetation cover.

The LULC- and NDVI-change analysis covered the North and South Wello zones over an area of 300,000 km^2. It applied a remote sensing approach, which used moderate resolution imaging spectrometer (MODIS) surface reflectance image and NDVI data composited at 8-day and 2-monthly intervals, respectively, between 2000 and 2010. The images were classified using supervised classification, and the NDVI data analyzed for spatio-temporal changes. The analysis showed remarkable changes, mainly improvement in grassland/woody grassland (increased by 14.6%) and in degraded woody vegetation (decreased by 13%). Similarly, the area covered by NDVI value >0.4 and 0.3 to 0.4 increased by 12.5% and 2.3%, respectively. The analysis also showed an increase of the NDVI value in the central parts of the study area, particularly along the highways, which indicates restoration. Conversely, remote parts were identified as degradation hotspots, i.e., NDVI decrease. On the other hand, comparison of the digital elevation model and the NDVI change analysis indicates that larger parts of the steep landscapes show vegetation restoration despite the continuing population growth. Thus, this change can be attributed to government policy. Policy implementation could be influenced by community awareness level, and activity of local stockholders such as local administration (village/*Kebele* and district/*Wereda*) and involvement of non-government organizations (NGOs).

The role of exclosure on natural resource restoration was studied not only in the LULC- and NDVI-change analysis but also regarding the impact on soil fertility restoration. Accordingly, the performance of exclosure in the soil fertility restoration evaluation at micro-watershed level was done in the Gubalafto *Wereda (*district) of the North Wello zone. The analysis used soil samples collected from exclosures (10- and 27-year-old), and control sites (open lands) in three landscape positions (upper, middle and lower) in the *Weyna-Dega* (mild) and *Dega* (cool) agro-ecological zones. Soil samples were collected from 20 m^2 plots at 1-m intervals along the sides and diagonals of the plots to 15 cm depth and composited. The composite samples were analyzed in the laboratory for selected physico-chemical properties using standard methods, and the data statistically tested using analysis of variance (ANOVA) in a general linear model (univariate) in SPSS 17. The analysis revealed significant soil fertility improvement. Soils of the exclosures had significantly higher organic carbon (OC) and total nitrogen (TN) contents than the open sites. However, the differences decreased with increase in age. Soils of the 10- and 27-year-old exclosures had significantly higher OC and TN contents than those on open sites, while insignificant differences were observed between exclosures. The OC and TN content differences between the control sites and the 10-year-old exclosures were 41% (6.7 g/kg) and 44% (0.7 g/kg), respectively, while differences between the 10- and 27-year-old exclosures were only 9% (2.1 g/kg) and 22% (0.5 g/kg), respectively, which indicates that the restoration rate reached a steady state with time. The soil fertility restoration also significantly varied with agro-ecological zone. Exclosures in the *Weyna-Dega* zone had significantly higher soil fertility restoration than those in the *Dega* zone. This could be attributed to the effect of agro-ecological zone (climate) on biomass production, vegetation type and organic matter addition and mineralization. Conversely, unlike in other studies, soil properties did not show significant differences across the terrain, which could be due to complemantary effect of mechanical SWC measures with exclosures. The mechanical structures enhance *in-situ* conservation which protect litter and soil erosion towards the lower landscape position especially in early period of exclosure.

An evaluation of the performance of farmland terracing regarding soil fertility and crop yield was conducted in the Maybar soil conservation research site (MSCRS) of the South Wello zone. The fixed MSCRS plots were categorized in four terrain slopes positions (3-5%, 5-8%, 8-15% and 15-30%); composite soil samples were collected from 16 plots representing different terrain positions and three terrace positions. The samples were analyzed for selected physico-chemical properties, and the results were statistically tested using analysis of variance (ANOVA) and compared with 1983 survey data. Yield data (grain and biomass) of seven crop types, namely barley, maize, wheat, emmer wheat, teff, horse bean and field pea collected between 1995 and 2009 from 40 fixed plots on three terrace positions (low-, mid- and up-) were statistically analyzed using a mixed linear model in SAS, and multiple pair-wise comparison was done using the Tukey-Kramer adjustment. The SWC measures led to clear biophysical changes such as terrain modification, improvement of soil depth, stability of active gullies and stream banks. Furthermore, farmland terracing helped to maintain soil fertility and crop productivity. Among the topsoil physico-chemical properties statistically tasted pH, EC, exchangeable K^+ and Na^+, OC and texture showed statistically significant differences across the terrain. Soil pH and exchangeable bases increased with decrease in slope. The increases were due to erosion and leaching of soluble salts from the upper slope and accumulation at the down-slope terrain. Terraces received higher organic matter input from the non-arable areas and showed 0.55% (5.5 g/kg) higher soil OC contents in positions located adjacent to these lands on the moderately steep (15 - 30%) slopes. As opposed to other studies, topsoil physico-chemical properties except bulk density showed insignificant differences within a terrace, i.e., no significant topsoil fertility differences. Soil bulk density at the mid- terrace position was 0.4 gm/cm^3 higher than at the other positions. With development of bench terraces, incoming runoff was uniformly distributed within a terrace, which reduced the soil fertility gradient. The uniform soil aggregate deposition resulted in packing of soil particles, thus the mid-terrase position had a significantly higher bulk density than the other positions. Although removal of soil nutrients through crop harvest continued, differences in soil nutrients with terrace age were non-significant. This indicates that terracing reduced soil nutrient loss through erosion. However, terracing alone does not improve the soil fertility.

The ultimate objective of farmland terracing is to improve and/or maintain crop production and productivity. Similar to the topsoil fertility level, crop production showed non-significant differences across the terrain. However, yields showed a decreasing trend with increase in slope of the terrain. The non-significant yield differences for most crops across the terrain indicate that terracing reduced soil erosion and nutrient translocation thereby reducing yield loss in the erosion zone. The yield gradient tendency across the terrain could be due to the soil erosion that had occurred before terracing, which influenced soil depth, thereby affecting nutrient and water storage capacity. Conversely, yields of all crops except wheat showed significant differences ($P \leq 0.002$) within a terrace. The yield decreased from the low-terrace towards the up-terrace positions. On average, the grain yield differences were 0.53 t ha^{-1} between the low- and up-terrace positions, 0.3 t ha^{-1} between low- and mid-terrace positions, and 0.24 t ha^{-1} between mid- and up-terrace positions. Unlike findings in other studies, the crop yield variation in this study could be due to the soil depth gradient, which was in same direction as the yield gradient. The soil depth gradient could in turn influence nutrient and soil-water storage. Terracing was introduced in the area while the common agricultural practices were continued. Fertility improvement measures are at a very low level or not at all, and fallowing has been considerably reduced. Crop yield was almost stable with increasing terrace age. This indicates that terracing reduced soil and nutrient loss through erosion, otherwise yields would have been significantly reduced under the continued production constraints and limited agricultural input use.

9.2 Overall conclusions

SWC interventions in general and farmland terracing and exclosure in particular have played a considerable role in maintaining and/or restoring soil fertility, crop production and productivity, restoring vegetation cover and ecological health, and in mitigating anthropogenic land degradation. This study show terracing and exclosure played a paramount role in reducing land degradation and/or restoring degraded lands. However, the interventions need improvement to maximize the benefit and balance peoples current and future needs. The main conclusions and recommendations are:

i. The LULC and NDVI analysis showed restoration in areas where exclosure was implemented. The exclosure helped to improve vegetation cover and soil fertility.

ii. Even if the population growth at the time of the study was at a slower rate than in previous censuses, it was still high as far as sustainable resources management is concerned, and agricultural lands have been increasingly fragmented. As a result, some farmers had a negative perception of exclosure as in their opinion it competed with grazing lands. Therefore, it is important to complement the natural resources conservation effort by family planning, implementation of non-agricultural economic options and use of alternative household energy sources beyond biomass.

iii. The impact of exclosure on vegetation and soil fertility restoration was immense, and the mechanical SWC measures had complemantary effects. The mechanical measures enhanced *in-situ* conservation and soil fertility restoration. Unlike in other studies, no soil fertility restoration gradient was observed across the terrain, which is a positive impact. Hence, it could be a wise approach to compliment exclosure with mechanical SWC structures in order to achieve a quick and efficient impact.

iv. On the other hand, the soil fertility restoration due to exclosure was nonlinear with agro-ecological zones, where higher restoration was observed in the *Weyna-Dega* (mild) than in the *Dega* (cool) zone. This could be attributed to the effect of climate (agro-ecological zone) on biomass production, vegetation types, and organic matter decomposition, which indicates the importance of considering the agro-ecological zone during exclosure planning.

v. In general, terracing had a number of advantages with respect to reducing soil and nutrient loss through erosion. However, terracing alone does not improve soil fertility, as fertility loss is not only through erosion. Furthermore, terracing cannot fully halt erosion. In order to improve soil fertility, terracing should be supplemented by appropriate organic and inorganic fertilizer application based on the site-specific soil fertility level.

vi. The regular terrace maintenance and sedimentation helped terraces to develop to bench terraces, which in turn reduced topsoil fertility gradients within a terrace. It was found that terracing was found more effective up to 15% slope terrain.

vii. The impact of terracing on crop production was in line with that on soil fertility. Like topsoil fertility, the crop yield did not show significant changes with terrace age, while nutrient removal through harvest continued, fallowing was reduced and there were no improvements in fertilizer use. This indicates that terracing at least helped to maintain topsoil fertility and thereby crop production, but terracing alone cannot significantly increase crop yields.

viii. Yield gradients within a terrace were observed. Therefore, to reduce the gradients, it is advisable to use site-specific soil fertility amendment levels.

ix. In some crops, terracing induced negative impacts at the lower terrain positions. This effect could be reduced through selecting appropriate crops in this position, particularly by excluding crops sensitive to water-logging and regularly drain accumulated water.

x. By and large, the current analysis clearly showed that SWC practices in general and farmland terracing and exclosure in particular played important role to halt land degradation and to restore degraded lands.

9.3 Research and policy implications

Land degradation is caused by various factors and has wide impacts. As a result, restoration measures aimed at restoring environmental and ecological health, which involves various factors. The factors could influence each other, where the results have interlinked outcomes. Thus, land degradation assessments need to use an interdisciplinary approach and broad data sets. The current study involved biophysical resource assessments using soil and crop yield data, and also temporal satellite data. It examined changes in soil fertility and crop production on farmlands due to terracing and also analyzed LULC and NDVI changes and soil fertility conditions due to exclosure. However, the subsequent follow-up studies are required to fully understand the processes, which could give information on how to maximize the restoration and outcomes of the conservation practices.

i. Although the regional state declared same policy measures concerning SWC and land management, the LULC and NDVI changes vary across districts. The vegetation improvement in some areas could be due to higher community awareness/experience and better local stakeholder commitments as well as NGO involvement. Discussions with community and agriculture offices indicated that prior SWC experience and NGO interventions enhanced the practices. However, the current study did not sufficiently address this aspect. Thus, further studies on the adoption of the practices and the factors that influence adoption are recommended.
ii. With increase of exclosure age, there is a gradual replacement of palatable species, as these are mainly higher-layer vegetation. This could result in livestock feed shortages, which would lead to further dependency on crop residues and to degradation of the limited grasslands and open areas. Hence, further research and improvement of livestock feed from exclosures is vital to assure sustainability, particularly studies on appropriate forage species that could perform well on degraded lands to replace the non-palatable species, and the design of optimal management strategies that maximize livestock feed and other uses from exclosures. This could improve the livelihoods of the rural households, who entirely depend on agriculture.
iii. During the field study, it was observed that most exclosures have neither management nor utilization plans. They should be planned with defined purposes such as soil conservation (reduced soil erosion, flood and landslide control), forage production, biodiversity conservation, apiculture and multipurpose (involving variety of uses). Planning also needs to include detailed management on how and when each activity is to take place rather than just taking corrective action. Therefore, we recommend that exclosures should be planned considering both the conservation and long- and short-term benefits of the community.
iv. The analysis of topsoil fertility did not show significant differences within a terrace; however, crop yield showed significant differences. The crops on lowterrace position showed higher yields and remained green for a longer time than those on the other positions. This could be related to the soil accumulation gradient, which caused a depth gradient. The gradient could have been established in the early stages of terrace development. Therefore, the yield gradient within a terrace could

be attributed to the soil depth, which results in differences in the soil-water and nutrient storage capacity. However, the current study did not investigate this aspect in detail. Thus, further studies on the volumetric soil-moisture and nutrient gradients within a terrace are recommended.

v. Studying the effects of terracing on crops sensitive to water-logging such as wheat could be important to minimize the negative effect thereby maximize the benefit of terracing. The findings could provide information on the impact of terracing under various soil types, crop types and terrain positions, and identify appropriate crops for different combinations of soil types and landscape positions.

vi. Terracing did not result in significant yield increases. The analysis showed that on average 6% of the total cultivable land is occupied by terraces, which indicates that this land is not available for crop production. In order to compensate the resulting yield loss, use of production-boosting technologies is indispensable. Hence, increased use of chemical and organic fertilizers (manure, compost, green manure) together with terracing is recommended. It is also important to mention that grass on the terraces provides livestock feed. In the mixed-crop-livestock farming systems, livestock production is important for the livelihoods of the rural households. Therefore, part of the farmland lost through terrace construction could be compensated by livestock feed production. In order to understand the impact of terracing on soil fertility and crop production, we recommend further research that considers controlled management practices and input utilization and involves intensive site-specific samplings.

REFERENCES

Alexander M (1991) Introduction to soil microbiology. Wiley, New York. Pp467

Al-Rumikhani YA (2002) Effect of crop sequence, soil sample location and soil depth on soil water holding capacity under center pivot irrigation. Agricultural Water Management, 55:93-104

Amsalu A, de Graaff J (2007) Determinants of adoption and continued use of stone terraces for soil and water conservation in an Ethiopian highland watershed. Ecological Economics, 61(2-3):294-302

Amsalu A, Stroosnijder L, Graaff J (2007) Long-term dynamics in land resource use and the driving forces in the Beressa watershed, highlands of Ethiopia. Journal of Environmental Management, 83(4):448-459

Angassa A, Oba G (2008) Herder perceptions on impact of range enclosures, crop farming, fir ban and bush encroachment on the rangelands of Borana, Southern Ethiopia. Human Ecology, 36(2):201-2015

Anonymous (1980) Ethiopian forest and wildlife conservation and development proclamation, Negarit Gazeta No. 192/1980, Addis Ababa, Ethiopia

Anonymous (2005) Federal Democratic Republic of Ethiopia rural land administration and use proclamation. Negarit Gazeta, No 456/2005, Addis Ababa, Ethiopia

Anonymous (2006) Amhara National Regional State Environmental Protection, Land Administration and Use Authority (ANRSEPLAA). The revised rural land administration and use determination proclamation, No. 133/2006, Bahir-Dar, Ethiopia, pp 11-70

ANRS-BFED (2008) Amhara National Regional State Bureau of Finance and Economics Development (ANRS-BFED), annual statistical bulletin, Bahir-Dar, Ethiopia, pp 29-50

Antoci A, Russu P, Ticci E (2009) Distributive impact of structural change: Does environmental degradation matter? Structural Change and Economic Dynamics, 20(4):266-287

Asefa DT, Oba G, Weladji RB, Colman JE (2003) An assessment of restoration of biodiversity in degraded high mountain grazing lands in northern Ethiopia. Land Degradation and Development, 14(1):25-38

Assen M, Nigussie T (2009) Land-use/cover changes between 1966 and 1996 in Chirokella micro-watershed, southeastern Ethiopia. East African Journal of Sciences, 3(1):1-8

Awulachew SB, Yilma AD, Loulseged M, Loiskandl W, Ayana M, Alamirew T (2007) Water resource and irrigation development in Ethiopia. International Water Management Institute, Working Paper No. 123, pp 4-9

Aynekulu E, Denich M, Tsegaye D (2009) Restoration response of *Juniperus procera* and *Olea europaea*, *subsp cuspidate* to exclosure in a dry afromontane forest in north Ethiopia. Mountain Research and Development, 29(2):143-152

Babulo B, Muys B, Nega F, Tollens E, Nyssen J, Deckers J, Mathijs E (2009) The economic contribution of forest resource use to rural livelihoods in Tigray, Northern Ethiopia. Forest Policy and Economics, 11(2):109-117

Baccini A, Laporte N, Goetz SJ, Sun M, Dong H (2008) A first map of tropical Africa's above-ground biomass derived from satellite imagery. Environmental Research Letters, 3(4)45011:1-9

Badege B (2001) Deforestation and land degradation in the Ethiopian highlands: A strategy for physical recovery. Northeast African Studies, ISSN 0740-9133, 8(1):7-26

Barbiéro L, Valles V, Régeard A, Cheverry C (2001) Residual alkalinity as tracer to estimate the changes induced by forage cultivation in a non-saline irrigated sodic soil. Agricultural Water Management, 50(3):229-241

Barrow CJ (1991) Land degradation: Development and breakdown of terrestrial environments. Cambridge University Press, ISBN 10:0521466156, pp 5-17

Bekele-Tesemma A, Birnie A, Tengnäs B (1993) Useful trees and shrubs for Ethiopia: Identification, propagation and management for agricultural and pastoral communities. Sweden

Belay K, Abebaw D (2004) Challenges facing agricultural extensions: A case study from South-western Ethiopia. African Development Review, 16(1):134-168

Bergmann W (1992) Nutritional disorders of plant: Development, visual and analytical diagnosis, New York

Bewket W (2007) Soil and water conservation intervention with conventional technologies in northwestern highlands of Ethiopia: Acceptance and adoption by farmers. Land Use Policy, 24:404-416

Bhan C (988) Spatial analysis of potential soil erosion risks in Wello region, Ethiopia: A geomorphological evaluation. Mountain Research and Development, 8(2-3):139-144

Bingxin Y, Nin-Pratt A, Funes J, Asrat S (2010) Cereal production and technology adoption in Ethiopia. International Food Policy Research (IFPRI). Discussion paper 1131, pp 3-10

Black CA (1965) Methods of soil analysis Part I, American Society of Agronomy. Madison, Wisconsin, USA

Bojö J, Cassells D (1995) Land degradation and rehabilitation in Ethiopia: A reassessment. AFTES, Working Paper No. 17, World Bank

Calviṅo PA, Sadras VO (1999) Inter-annual variation in soybean yield: Interaction among rainfall, soil depth and crop management. Field Crops Research, 63(3):237-246

Cao S, Chen L, Feng Q, Liu Z (2007) Soft-riser bench terrace design for the hilly loess region of Shaanxi province, China. Landscape and Urban Planning, 80(1-2):184-191

Carla K, Arnaud M, Jacques M (2003) Spontaneous vegetation dynamics and restoration prospects for limestone quarries in Lebanon. Applied Vegetation Sciences, 6(2):199-204

Catherine P, Ouimet R (2007) Organic carbon matter and bulk density relationships in forest soils. Canadian Journals of Soil Sciences, 88(3):315-325

Chen ZS, Hsieh CF, Jiang FY, Hsieh TH, Sun IF (1997). Relations of soil properties to topography and vegetation in a subtropical rain forest in southern Taiwan. Plant Ecology, 132(2):229-241

Ciampalini R, Billi P, Ferrari G, Borselli L (2008) Plough marks as a tool to assess soil erosion rates: A case study in Axum (Ethiopia). Catena, 75(1):18-27

Coltorti M, Dramis F, Ollier CD (2007) Plantation surfaces in northern Ethiopia. Geomorphology, 89(3-4):287-296

CSA (2008) Summery and statistical report of the 2007 population and housing censes: Population size by age and sex, United Nation Population Fund (UNFPA). Addis Ababa, Ethiopia, pp 7-19

Cuffaro N (1997) Population growth and agriculture in poor countries: A review of theoretical issues and empirical evidence. World Development, 25(7):1151-1163

de Sherbinin A, Carr D, Cassels S, Jiang L (2007) Population and environment, annual reviw, Enviromental Resources, Springer ISSN: 1573-7810, 11111(32):345-573

Dejene A (1990) Environmental, famine and politics in Ethiopia: A view from the village. London, pp 1-128

Dercon G, Deckers J, Govers G, Poesen J, Sánchez H, Vanegas R, Ram´ırez M, Loaiza G (2003) Spatial variability in soil properties on slow-forming terraces in the Andes region of Ecuador. Soil and Tillage Research, 72(1):31-41

Descheemaeker K, Mapedza E, Amede T, Ayalneh W (2010) Effects of integrated watershed management on livestock water productivity in water scarce areas in Ethiopia. Physics and Chemistry of the Earth, 35(13-14):723-729.

Descheemaeker K, Muys B, Nyssen J, Sauwens W, Haile M, Poesen J, Raes D, Deckers J (2009) Humus from development during forest restoration in exclosures of the Tigray Highlands, Northern Ethiopia. Restoration Ecology, 17(2):280-289

Descheemaeker K, Muys B, Nyssen J, Poesen J, Raes D, Haile M, Deckers J (2006) Litter production and organic matter accumulation in exclosures of the Tigray, Ethiopia. Forest Ecology and Management, 233(1):21-35

Dong D, Ramsey MH, Thornton I (1995) Effect of soil pH on Al availability in soils and its uptake by the soybean plant (*Glycine max*). Journal of Geochemical Exploration, 55(1-3):223-230

Dregne HE (1990) Erosion and soil productivity in Africa. Journal of Soil and Water Conservation, 45(4):431-436

Dubale P (2001) Soil and water resources and degradation factors affecting productivity in Ethiopian highland agro-ecosystems. Northeast African Studies, ISSN 0740-9133, 8(1):27-52

EFAP (Ethiopian Forestry Action Program) (1994) Ministry of Natural Resources Development and Environmental Protection, Volume 2 and 3, Final Report, EFAP Secretariat, Addis Ababa

Ehret C (1979) On the antiquity of agriculture in Ethiopia. Journal of African History, 20(2):161-177

El-Swaify SA (1997) Factors affecting soil erosion hazards and conservation needs for tropical steep lands. Soil Technology, 11(1):3-16

Eshatu Z (2004) Natural $_{15}$N abundance in soils under young-growth forests in Ethiopia. Forest Ecology and Management, 187(2-3):139-147

FAO (2006) Guidelines for soil description, 4th edition. Rome, Italy, pp 4-5

FAO (2004) Methodological framework for land degradation assessment in dry-lands. ftp://ftp.fao.org/agl/agll/lada/LADA-Methframwk-simple.pdf. Cited 12 Feb 2011 Organization site

FAO (2001) Global forest resource assessment 2000. FAO forestry paper, pp 1-140

FAO (2000) Land covers classification system (LCCS): Classification concepts and user manual. http://www.fao.org/docrep/003/x0596e/x0596e00.htm Cited 12 Feb 2011 Organization site

FAO (1986) Ethiopian highland reclamation study (EHRS). Land Use Planning and Regulatory Department, Ministry of Agriculture, FAO, Final report, Vol. 1 and 2, Rome

FAO (1984) Ethiopian geomorphology and soils (1:1,000,000 scales). Assistance to Land Use Planning, Addis Ababa, Ethiopia, np

Feller C, Beare MH (1997) Physical control of soil organic matter dynamics in the tropics. Geoderma, 79(1-4):69-116

Feoli E, Vuerich LG, Zerihum W (2002) Evaluation of environmental degradation in northern Ethiopia using GIS to integrate vegetation, geomorphological, erosion and socio-economic factors. Agriculture, Ecosystems and Environment, 91(1-3):313-325

FRA (2005) Global forest resource assessment (FRA): 15 key findings. http://www.fao.org/forestry/foris/data/fra2005/kf/common/GlobalForest A4. Cited 20 Mar 2010 FAO site

Franzluuebbers AJ, Haney RL, Honeycutt CW, Arshad MA, Schomberg HH, Hons FM (2001) Climatic influences on active fractions of soil organic matter. Soil Biology and Biochemistry, 33(7):1103-1111

Fu B, Liu S, Chen L, Lu Yi, Qiu J (2003) Soil quality regime in relation to land cover and slope position across a highly modified slope landscape. Ecological Research, 19(1):111-118

Fu H, Pei S, Changgui Wan C (2008) Changes in soil properties and vegetation following exclosure and grazing in degraded Alxa desert steppe of Inner-Mongolia, China. Agriculture, Ecosystems and Environment, 124(1-2):33–39

Gabrielle B, Da-Silveira J, Houot S, Michelin J (2005) Field-scale modeling of carbon and nitrogen dynamics in soils amended with urban waste composts. Agriculture, Ecosystems and Environment, 110(3-4):289-299

Gebermichael D, Nyssen J, Poesen J, Deckers J, Haile M, Govers G, Moeyersons J (2005) Effectiveness of stone bunds in controlling soil erosion on cropland in the Tigray highlands, northern Ethiopia. Soil Use and Management, 21(3):287-297

Gebreegziabher T, Nyssen J, Bram G, Fekadu G, Behailu M, Haile M, Deckers J (2009) Contour furrows for *in-situ* soil and water conservation, Tigray, Northern Ethiopia. Soil and Tillage Research, 103(2):257-264

Ghobadi ME, Ghobadi M (2010) Effect of anoxia on root growth and grain yield of wheat cultivars. World academy of Science, Engineering and Technology, 70:85-88

Goldammer JG (2002) The Ethiopian wild-land fire emergency 2000: Lessons learnt and consequences for improved cooperation in Sub-Saharan Africa. Paper presented at UN regional workshop on the use of space technology for disaster management for Africa, Addis Ababa, Ethiopia, np

Gonfa L (1996) Climatic classification of Ethiopia. Addis Ababa, Ethiopia, pp 15-58

Haileslassie A, Priess J, Veldkamp E, Teketay D, Lensschen JP (2005) Assessment of soil nutrient depletion and its spatial variability on smallholders' mixed farming systems in Ethiopia using partial versus full nutrient balances. Agriculture, Ecosystems and Environment, 108(1):1-16

Hamza MA, Anderson WK (2002) Improving soil physical fertility and crop yield on a clay soil in Western Australia. Australian Journal of Agricultural Research, 53(5):615-620

Hay RKM (1995) Harvest index: a review of its use in plant breeding and crop physiology. Annals of Applied Biology, 126(1):197-216

Hengsdijk H, Meijerink GW, Mosugu ME (2005) Modeling the effect of three soil and water conservation practices in Tigray, Ethiopia. Agriculture, Ecosystems and Environment, 105(1-2):29-40

Herweg K, Ludi E (1999) The performance of selected soil and water conservation measures-case studies from Ethiopia and Eritrea. Catena, 36(1):99-114

Hill MJ, Donald GE (2003) Estimating spatio-temporal patterns of agricultural productivity in fragmented landscape using AVHRR NDVI time series. Remote Sensing of Environment, 84(3):364-384

Hurni H (1998) Agro-ecological belts of Ethiopia: Explanatory notes on three maps at a scale of 1:1,000,000. Research report, Soil Conservation Research Program. Addis Ababa, Ethiopia, pp 3-20

Hurni H (1993) Land degradation, famines and resource scenarios in Ethiopia. In: Pimentel (ed.) World soil erosion and conservation. Cambridge University Press, pp27-62

Hurni H (1988) Principles of soil conservation for cultivated land. Soil Technology, 1(2):1001-116.

Hurni H (1987) Erosion–productivity–conservation systems in Ethiopia. Proceedings of the fourth international conference on soil conservation. Maracy, Venezuela, pp2-20

Hurni H (1983) Ethiopian highlands reclamation study. Soil formation rates in Ethiopia, Working Paper No. 2, Addis Ababa, Ethiopia

Jahnke HE (1982) Livestock production systems and livestock development in tropical Africa. Kiel Wissenschaftsverlag, Vauk: Kiel, pp 79-81

Jansen LJM, Gregorio AD (2003) Land-use data collection using the land cover classification system, results from a case study in Kenya. Land Use Policy, 20(2):131-148

Kaihura FBS, Kullaya IK, Kilasara M, Aune JB, Singh BR, Lal R (1999) Soil quality effects of accelerated erosion and management systems in three eco-regions of Tanzania. Soil and Tillage Research, 53(1):59-70

Kalinin O, Goryachkin SV, Karavaeva NA, Lyuri DI, Najdenko L, Giani L (2009) Self-restoration of post-agrogenic sandy soils in the southern Taiga of Russia: Soil development, nutrient status, and carbon dynamics. Geoderma, 152(1-2):35-42

Kariuki M, Kooyman RM, Smith RGB, Wardell-Johnson G, Vanclay JK (2006) Regeneration changes in tree species abundance, diversity and structure in logged and unlogged subtropical rainforest over a Thirty-Six-Year Period. Forest Ecology and Management, 236(2-3):162-176

Kaufmann M, Tobias S, Schulin R (2010) Comparison of critical limits for crop plant growth based on different indicators for the state of soil compaction. Plant Nutrition and Soil Science, 173(4):573-583

Keller T, Håkansson I (2010) Estimation of reference bulk density from soil particle distribution and soil organic matter content. Geoderma, 154(3-4):398-406

Kelley HW (1983) Keeping the land alive: Soil erosion-its causes and cures. FAO Soils Bulletin No 50, Rome

Khater C, Arnaud M, Jacques M (2003) Spontaneous vegetation dynamics and restoration prospects for limestone quarries in Lebanon. Applied Vegetation Science, 6(2):199-204

Koch W, Pülschen L (1990) The significance of soil burning (´´Guie´´) in Ethiopia with special regard to its effects on the Agrestal weed flora. Agronomy and Crop Science, 164(4):254-261

Lambin EF, Geist HJ, Lepers E (2003) Dynamics of land-use and land-cover change in tropical regions. Annu. Rev. Environ. Resour, 28:205-241

Lawrence FB, Bruce JG (2005) Interacting effects of temperature, soil moisture and plant biomass production on ecosystem respiration in a northern temperate grassland. Agriculture and Forest Meteorology, 130(3-4):237-253

Lemenih M, Karltun E, Olsson M (2005) Soil organic matter dynamics after deforestation along a farm field chronosequence in southern highlands of Ethiopia. Agriculture, Ecosystems and Environment, 109(1-2):9-19

Lillesand TM, Kiefer RW, Chipman JW (2004) Remote sensing and image interpretation, 4th ed, New York

Logan WEM (1946) An introduction to the forests of central and southern Ethiopia. Imperial Forestry Institute of Oxford, paper 24.

Loveland P, Webb J (2003) Is there a critical level of organic matter in the agricultural soils of temperate regions: A review. Soil and Tillage Research, 70(1):1-18

McCann JC (1995) Peoples of the plow: An agriculture history of Ethiopia, 1800-1990. The Journal of Modern African Studies, 34(2):361-362

McIntosh PD, Allen RB, Scott N (1997) Effects of exclosure and management on biomass and soil nutrient pools in seasonally dry high country, New Zealand. Journal of Environmental Management, 51(2):169-186

McPherron SP, Alemseged Z, Marean CW, Wynn JG, Reed D, Greaads D, Bobe R, Bearat HA (2010) Evidence of stone-tool-assisted consumption of animal tissues before 3.9 million years ago at Dikika, Ethiopia. Nature, 446(7308):857-860

Mekonnen A, Bluffstone R (2008) Policies to increase forest cover in Ethiopia. In: Bane et al. (eds), Proceeding of a policy workshop organized by EEPEF (Environmental Economics Policy Forum for Ethiopia) and EDRI (Ethiopian Development Research Institute), Addis Ababa, Ethiopia, pp23-68

Mekuria W., Veldkamp E, Tilahun M, Olschewski R (2011) Economic valuation of land restoration: The case of exclosures established on communal grazing land in Tigray, Ethiopia. Land Degradation and Development, 22(3):334-344

Mekuria W, Veldkamp E, Haile M, Nyssen J, Muys B, and Gebrehiwot K (2007) Effectiveness of exclosures to restore degraded soils as a result of overgrazing in Tigray, Ethiopia. Journal of Arid Environments, 69(2):270-284

Moges A, Holden NM (2008) Soil fertility in relation to slope position and agricultural land use: A case study of Umbulo catchment in southern Ethiopia. Ecological Research, 42(5):111-118

Nana-Sinkam SC (1995) Land and environmental degradation and desertification in Africa, ECA/FAO. http://www.fao.org/docrep/X5318E/x5318e02.htm. Cited 20 Mar 2010 FAO site

NBCBN-RE (Nile Basin Capacity Building Network- for River Engineering) (2005) Assessment of the current state of the Nile basin reservoir sedimentation problems. River morphology research cluster, pp 1-2

Nearing MA, Kimoto A, Nichols MH, Ritchie JC (2005) Spatial patterns of soil erosion and depositions in two small, semiarid watersheds. Journals of Geophyical Research, 110, F04020, doi: 10.1029/2005JF000290, pp1-11

NMSA (National Meteorological Services Agency of Ethiopia) (1996) Climatic and agro-ecology resources of Ethiopia, Addis Ababa, Ethiopia, 1(1):0-137

Nyssen J, Poesen J, Deckers J (2009) Land degradation and soil and water conservation in tropical highlands. Soil and Tillage Research, 103(2):197-202

Nyssen J, Poesen J, Gebremichael D, Vancampenhout K, D'aes M, Yihdego G, Govers G, Leirs H, Moeyersons J, Naudts J, Haregeweyn N, Haile M, and Deckers J (2007) Interdisciplinary on-site evaluation of stone bunds to control soil erosion on cropland in Northern Ethiopia. Soil and Tillage Research, 94(1):151-163

Nyssen J, Haregeweyn N, Descheemaeker K, Gebremichael D, Vancampenhout K, Poesen J, Haile M, Moeyersons J, Buytaert W, Naudts J, Deckers J, and Govers G (2006) Letter to the Editor, Comment on ''Modeling the effect of soil and water conservation practices in Tigray, Ethiopia'' [Agric. Ecosyst. Environ. 105(2005)29-40]. Agriculture, Ecosystems and Environment, 114(2-4):407-411

Nyssen J, Poesen J, Moeyersons J, Deckers J, Haile M, Lang A (2004) Human impact on the environment in the Ethiopian and Eritrean highlands: A state of the art. Earth-Science Reviews, 64(3-4):273-320

Oba G, Abebe MH, Angassa A, Weladji RB (2006) The role of area enclosures and fallow age in the restoration of plant diversity in northern Ethiopia. African Journals of Ecology, 44(4):507-514

Oba G, Post E, Syvertsen PO, Stenseth NC (2000) Bush cover and range condition assessments in relation to landscape and grazing in southern Ethiopia. Landscape Ecology, 15(6):535-546

Olarieta JR, Rodrı´guez-Valle FL, Tello E (2008) Preserving and destroying soils, transforming landscapes: Soils and land-use changes in the valley`s county (Catalunya, Spain) 1853–2004. Land Use Policy, 25(4):474-484

Olgun M, Kumlay AM, Adiguzel MC, Caglar A (2008) The effect of water-logging in wheat (T.aestivum L.). Acta Agriculturae Scandinavica Section B- Soil and Plant Science, 58(3):193-198

Olsen SR, Colo CV, Watenable FS, Dean LA (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular

Omiti JM, Parton KA, Sindena JA, and Ehui SK (1999) Monitoring changes in land-use practices following agrarian de-collectivization in Ethiopia. Agriculture, Ecosystems and Environment, 72(2):111-118

Oorts K, Vanlauwe B, Merckx R (2003) Cation exchange capacity of soil organic matter fractions in a Ferric Lixisols with different organic matter inputs. Agriculture, Ecosystems and Environment, 100(2):161-117

Pandey CB, Srivastava RC (2009) Plant available phosphorus in home garden and native forest soils under high rainfall in an equatorial humid tropic: a review. Plant Soil, 316(1-2):71-80

Pimentel D, Harvey C, Resosudarmo P, Sinclair K, Kurz D, McNair M, Crist S, Shpritz L, Fitton L, Saffouri R, Blair R (1995) Environmental and economic costs of soil erosion and conservation benefits. Science, 267(5201):1117-1123

Pohjonen V, Pukkala T (1990) *Eucalyptus globulus* in Ethiopian forestry. Forest Ecology and Management, 36(1):19-31

Prasannakumar V, Vijith H, Abinod S, Geetha N (2012) Estimation of soil erosion risk within a small mountainous sub-watershed in Kerala, India, using revised universal soil loss equation (RUSLE) and geo-information technology. Geoscience Frontiers, 3(2):209-215

Puhr CB, Donoghue DNM (2000) Remote sensing of upland conifer plantations using Landsat TM data: A case study from Galloway, south-west Scotland. International Journal of Remote Sensing, 21(4):633-646

Rasool R, Kukal SS, Hira GS (2007) Soil physical fertility and crop performance as affected by long term application of FYM and inorganic fertilizers in rice-wheat system. Soil and Tillage Research, 96(1-2):64-72

Richter DD, Markewitz D, Trumbore SE, Carol G, Wells CG (1999) Rapid accumulation and turnover of soil carbon in a re-establishing forest. Nature, 400:56-58

Riebsame WE, Meyer WB, Turner BL (1994) Modeling land use and cover as part of global environmental change. Climate Change, 28(1-2):45-64

Rowell DL (1994) Soil science: Method and applications. Addison Wesley Longman Limited England

Sariyildiz S, Akkuzu E, Kucuk M, Duman A, Aksu Y (2008) Effect of Ips typographus (L) damage on litter quality and decomposition rates of Oriental Spruce [Picea Orientalis (L.) Link.] in Hatila Valley National Park, Turkey. European Journal of Forest Research, 127(5):351-360

Scherr SJ (1999) Soil degradation, a threat to developing-country food security by 2020? Food, agriculture and the environment discussion paper 27. International Food Policy Research Institute 2033 K Street, N.W. Washington DC 20006-1002 USA, pp 13-45.

Scherr SJ (2000) A downward spiral? Research evidence on the relationship between poverty and natural resource degradation. Food Policy, 25(4):479-498

SCRP (Soil Conservation Research Programme) (2000) Area of Maybar, Wello Ethiopia, long term monitoring of the agricultural environment (1981-1994). Soil erosion and conservation data base. Switzerland, pp 2-36

Shiferaw B, Holden ST (1999) Soil erosion and smallholders' conservation decisions in the highlands of Ethiopia. World Development, 27(4):739-752

Shiferaw B, Holden ST (1998) Resource degradation and adoption of land conservation technologies in the Ethiopian highlands: A case study in Andit Tid, North Shewa. Agricultural Economics, 18(3):233-247

Sonneveld BGJS, Keyzer MA (2003) Land under pressure: Soil conservation concerns and opportunities for Ethiopia. Land Degradation and Development, 14(1):5-23

Sørensen PN, Bekele S (2009) Nice children don't eat a lot of food: Strained livelihoods and the role of aid in north Wollo, Ethiopia. Forum for Social Studies, Addis Ababa, Ethiopia, pp 5-230

Spielman DJ, Kelemwork D, Alemu D (2011) Seed, fertilizer, and agricultural extension in Ethiopia. Ethiopian strategy support program (ESSP II), Working Paper No. 20, pp 4-8

Stocking M, Murnaghan N (2000) Land degradation guidelines for field assessment. http://archive.unu.edu/env/plec/l-degrade/index-toc.html. Cited 15 Mar 2010 UN University site

Sys C, Ransi V, Debaveye J, Beernaert F (1993) Land evaluation, Part III, Crop Requirements. Agriculture Publication No. 7, ITC, Ghent, pp 7-178

Tadesse G (2001) Land degradation: A challenge to Ethiopia. Journal of Environmental Management, 27(6):815-824

Tamene L, Vlek PLG, Park SJ, Dikau R (2006) Analysis of factors determining sediment yield variability in the highlands of northern Ethiopia. Geomorphology, 76:76-91

Tefera B, Ayele G, Atnafe Y, Jabbar MA, Dubale P (2002) Nature and causes of land degradation in the Oromiya Region: A review. Socio-economic and policy research, Working Paper No. 36, International Livestock Research Institute (ILRI), Nairobi, Kenya, pp 18-35

Tefera M, Chernet T, Harro W (1996) Explanation on geological map of Ethiopia a 1:2,000,000 scale. Bulletin No 3, Addis Ababa, Ethiopia, pp 2-64

Tekle K (1999) Land degradation problems and their implications for food shortage in south Wello, Ethiopia. Environmental Management, 23(4):419-427

Terrill C (1986) Ethiopia: Children of the drought. Elsevier Science Ltd. 328(8508): 681-681

Tesfaye K, Walker S (2004) Matching of crop and environment for optimal water use: The case of Ethiopia. Physics and Chemistry of the Earth, 29(15-18):1061-1067

Tilahun K (2006) Analysis of rainfall climate and evapo-transpiration in arid and semi-arid regions of Ethiopia using data over the last half a century. Journal of Arid Environments, 64(3):474-487

Turner BL, Shajaat Ali AM (1996) Induced intensification: Agricultural change in Bangladesh with implications for Malthus and Boserup. Proceedings of the National Academy of Sciences of the United States of America, 93(25):14984-14991

UN (2007) World population properties: The 2006 revision highlights. New York

USAID (2008) Ethiopia biodiversity and tropical forest 118/119 assessment. EPIQ IQC: EPP-I-00-03-00014-00, Task Order 02. http://www.encapafrica.org/documents/biofor/Ethiopia2008. Cited 15 Mar 2010

Van Reeuwijk LP (2002) Procedures for soil analysis, 6th edition. ISRIC, Wageningen, The Netherlands. Technical paper 9

Vancampenhout K, Nyssen J, Gebremichael D, Deckers J, Poesen J, Haile M, Moeyersons J (2006) Stone bunds for soil conservation in the northern Ethiopian highlands: Impacts on soil fertility and crop yield. Soil and Tillage Research, 90(1-2):1-15

Vlek PLG, Le BQ, Tamene L (2008) Land decline in land-rich Africa. A creeping disaster in the making. Center for development research (ZEF) University of Bonn, Science Council and CGIAR, pp 12-54

Walkley A, Black CA (1934) An examination of Degtjareff methods for determining soil organic matter and the proposed modifications of the chromic acid titration method. Soil Science, 37:29-38

Wallace KJ (2007) Classification of ecosystem services: Problems and solution. Biological Conservation, 139(3-4):235-246

Wassie A, Sterck FJ, Teketay D, Bongers F (2009) Effects of livestock exclusion on tree regeneration in church forests of Ethiopia. Forest Ecology and Management, 257(3):765-772

Watson EE, Currey J (2009) Living terraces in Ethiopia: Konso landscape, culture and development. Eastern African Series

Watson M, Mullen R (2007) Understanding Soil Tests for Plant-Available Phosphorus. http://ohioline.osu.edu/agf-fact/. Cited 25 January 2011

Weigel G (1986) Soil map of the Maybar research area. Soil Conservation Research Programme, CDE, Berne, Switzerland, pp 1-104

Woldesemait B (1983) Some spatial characteristics of peasant farming in Ethiopia. Ethiopian Journal of Development Research, 5(7):17-48

World Bank (2011) World development report: conflict, security and development. http://wdr2011.worldbank.org/sites/default/files/pdfs/%20WDR2011_Full_Text. Cited 08 Aug 2011 Organization site

WRB (2006) World Reference Base (WRB) for soil resource, a framework for international correlation and communication, No 103. Part of world soil resource report No. 84. Rome, Italy, pp 67-97

Xu JM, Tang C, Chen ZL (2006) The role of plant residues in pH change of acid soils differing in initial pH. Soil Biology and Biochemistry, 38(4):709-719

Zhang Q, Fua B, Chen L, Zhaoa W, Yang Q, Liu G, Gulinck H (2004) Dynamics and driving factors of agricultural landscape in the semiarid hilly area of the Loess Plateau, China. Agriculture, Ecosystems and Environment, 103(3):535-543

Zhao H, Zhang X, Xu S, Zhao X, Xie Z, Wang Q (2010) Effect of freezing on soil nitrogen mineralization under different plant communities in a semi-arid area during a non-growing season. Applied Soil Ecology, 45(3):187-192

ACKNOWLEDGEMENT

I have received great support from different institutions and individuals during my PhD study. I am grateful to the Church Development Service (Evangelischer Entwicklungsdienst, EED) for providing me with a scholarship and supporting my research. I would also like to thank the Center for Development Research (Zentrum für Entwicklungsforschung, ZEF) of Bonn University for also financing my research, providing valuable support and hosting me during my study, and also the Dr. Hermann Eiselen Doctoral Programm of the Foundation Fiat Pains for their financial support for my research.

My sincere gratitude goes to my first supervisor Prof. Dr. Paul L.G. Vlek for accepting me as his student and for his support through the entire study and his review of my thesis. I would also like to thank Prof. Dr. Armin Skowronek to be my second supervisor. Further, my sincere thanks go to Dr. Lulseged Tamene for his valuable guidance and advice, his continued support and encouragement during the field research, write-up and his review of my thesis.

I would also like to thank the ZEF doctoral program administration, especially Dr. Günter Manske, for the administrative and technical support throughout my study. Special thanks go to Mrs. Rosemarie Zabel for her unreserved administrative support. My thanks also go to Mr. Guido Lücheters for his guidance during the statistical analysis.

The Sirinka research center of the agricultural research institute of the Amhara region, Ethiopia, is sincerely thanked for providing data and cooperation during the field study. The North Wello and South Wello zones and the respective district agriculture and rural development as well as the administration council offices and staffs are also thanked for providing secondary data and support during the field research. I would also like to extend my sincere thanks to the Generation Integrated Rural Development Consultants (GIRDC) for providing me with equipment and an office free of charge during field research. I would like to thank the Ethiopian National Soils Testing Laboratory and staff for on-time soil sample analysis. My special thanks go to Mr. Toshome Afrasa, managing director of GIRDC, for his all-round support and motivation. My sincere thanks go to Ethiopian Orthodox Church, Development and Inter Church Aid Commission and Dr. Nigussu Legesse for the support during the scholarship processes. I am also most grateful to Mr. Ali Ahmed, Mr. Zerihun Demissie and Mr. Alemu Tadesse for their support during my field research.

I would like to extend my deep thanks to my wife Ejigayehu Mengesha for handling all burdens and managing the family. It was really difficult to accomplish my study in the absence of her support and motivation. I very much thank my children Michael Shimeles and Kalab Shimeles for tolerating my absence. I am also grateful to my mother Engdawork Habte-Mariam, who laid the foundation for my schooling. I would also like to show gratitude to my sisters and brothers Mulumebet Mengesha, Atsede, Solomon, Aynalem, and Meaza, Amsale Mengesha, and Zewdu Melake-Tehay for their support and taking care of my family.

" Glory to God the Almighty "